# Asian High-Tin Bronzes
## Production Technology and Regional Characteristics

# 英　文

## - English Translation -

## A Preliminary Study on Ancient Copper Vessels in Japan

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### *1. The Origins of Metal in Japan*

In Japan, the Neolithic Period is divided into two periods. First part is called the "Jomon Period". The Jomon Period is dated from 12,000 BC to 700 ～ 500 BC. Metal was not used in this period. Only the site of Misakiyama, Yuza, Akumi in Yamagata Prefecture yielded a Chinese Yin Period bronze knife. However, this knife was discovered by accident and excavation reports have not been published yet. Therefore the artifact still remains a mystery.

In the Yayoi Period, bronze objects and iron objects began to be used. However it is not clear whether metal was already used at the beginning of the Yayoi Period or not because of the following reason. It was generally agreed that the Yayoi Period began around 3rd century BC (or the late 2nd century BC). However recent excavations at Early Yayoi Period sites, tree-ring dating of excavated woods, and radio-carbon dating particularly on charcoals on the surface of pottery reveal that the Yayoi Period probably dates back to 5th century BC to 7th century BC. There are still different opinions on the date of the beginning of the Yayoi Period among scholars because of methodological problems. I do not make any comments on this matter here because I do not study the Yayoi Period.

In the Early Yayoi Period, most of the bronze objects were imported. They include mirrors, dagger-axes and halberds. They were produced by casting. No forged bronze objects were discovered from Early Yayoi Period sites. Some of the bronze objects were produced by casting in Japan. Iron objects used in the Early Yayoi Period include casted iron axes, forged iron weapons and forged iron tools.

In the Late Yayoi Period, the bronze bell called Dotaku appeared in Japan. Dotaku is unique to Japan and over 500 Dotaku have been discovered. Although Japanese Dotaku originated from the small bronze bell in the Korean Peninsula and northeastern China, the former is several times larger than the latter in size (The largest Dotaku discovered in Yasu is 25 times bigger than the small bronze bell in height). Dotaku was also produced by casting. Bronze mirrors were intensively burnished after the casting. The mirror surface of the mirror was carefully smoothed and has no scars although traces left by grinding can often be observable on the edge and ventral surface of the mirror. Traces left by grinding can be observable both on domestic mirrors and imported mirrors. Although these traces are very useful for understanding the production techniques, it is not still clear whether the domestic mirrors and imported mirrors were ground with the same techniques or not because of the limited studies. However, these traces suggest that these mirrors were smoothed and burnished with a hand scraper and grinding stone rather than with a grinding wheel and grinding stone. In the Kofun Period, mirrors were smoothed and burnished in the same way. In the Heian Period, some of the domestic mirrors were still smoothed and burnished with a hand scraper and grinding stone.

In the Late and Final Kofun Periods, new copper objects such as bowls and footed plates (They are made of cooper alloys) first appeared in Japan. According to the study by Toshihiko MORIMITSU, 90 copper vessels had been discovered from the Kofun Period sites before 1978. After his study, more copper vessels were excavated from Kofun burial mounds[1)].

So far copper vessels excavated from Kofun burial mounds have been intensively studied. However, before around 1970, the copper vessels had not been studied in a systematic way. But the discovery of the late 6th century copper jug with a lid from the burial mound of Kannonyama Kofun, Takasaki in Gunma Prefecture gathered much attention because the jag is morphologically similar to 7th and 8th century Buddhist copper jugs stored at Horyuji temple and Shosoin, Todaiji temple. The jug is tall and has a beautifully shaped base. The base is thick and its bottom is only slightly concave. The bottom of the main body is also thick. The shape of outer and inner faces of the bottom suggest that the main body and base of the jug were separately casted and then jointed together into one piece. The lid has a ball on the top. The lid also has two bar springs on the ventral face, which prevents easy separation of the lid from the jug[2)].

This jug is the first discovered late 6th century jug in Japan. The results of qualitative analysis on the composition of the jug were published in the excavation report. According to the report, the jug was made of copper-lead-tin alloy. The jug was probably used as a container of perfume.

However the 6th century jug excavated from Kannonyama Kofun and the 7th century Buddhist jugs stored at Horyuji temple are different in the composition. Although both of the jugs has an egg shaped main body and lid with springs, the jugs stored at Horyuji temple are made of copper-tin alloy called “Sawari”. It suggests the shift from copper-lead-tin alloy to copper-tin alloy in the raw material for the production of jugs. The main body and base of the jugs stored at Horyuji temple were casted together in the same mold and burnished with a grinding wheel. The jugs stored at Horyuji temple are essentially different from the late 6th century jug excavated from Kannonji Kofun in this point[3)].

### *2) Buddhist Temples and Copper Alloy Vessels*

In Japan, the oldest copper vessels were excavated from Kofun burial mounds. However it is noteworthy that the Kinki region, where large Kofun burial mounds are concentrated, yielded a few copper bowls.

In contrast, the Kanto and Tohoku regions yielded more copper bowls than the Kinki region. This is probably because the number of large Kofun burial mounds decreased in the Kinki region in 7th century while the construction of large Kofun burial mounds began in Kanto region in 7th century. Omishinkanji Kofun in Saitama Prefecture and Kamifusa Kinreidzuka Kofun in Chiba Prefecture are typical examples of the large 7th century Kofun burial mounds in the Kanto region.

As for Nara and Heian Periods copper vessels, they were mostly excavated from remains of Buddhist temples or have been stored at Buddhist temples such as Shosoin. Copper vessels were also used as cremation ossuaries in Buddhism. This can be related to containers for the bones of the Buddha buried under pagodas.

In Shosoin, Todaiji temple, most of the Sawari bowls and Sawari spoons are stored in the southern storehouse. The central storehouse and southern storehouse in Shosoin store treasures related to the consecration of the Giant Buddha statue. They also store treasures transported from other buildings[3)]. Therefore late 7th century to 8th century Sawari objects stored at Buddhist temples such as Horyuji temple and Todaiji temple are probably related to the Buddhism. The Sawari vessels are usually divided into several types as follows. Artifacts other than vessels are also added to the following list by the author[4)].

| | | |
|---|---|---|
| Serving vessel | Serving bowl | bowl |
| | | Large bowl |
| | Saucer | |
| | Cup | |
| | Spoon/Scoops/Chop sticks | |
| | /Serving table | |
| Storage Vessel | Jar | |
| | Jug | |
| Others | Iron | |
| | Incense container with a handle | |
| | Footed incense container | |
| | Ossuary | |
| | Standard (e.g. Dragon Headed rod) | |
| | Bell | |

In addition, copper was also used as constructional materials and decoration materials in Buddhist temples.

The constructional materials include various components of the pagoda finial such as Kurin, Suien, Fukubachi and Roban. The decoration materials include various decoration plaques on the end of roof rafters, tail rafters and verge boards Copper was also used to connect topmost members of three-railed balustrades.

It is likely that the use of copper vessels became more valued in Buddhist temples through the use of copper for the construction of temples.

The text of “Daianji Garan Narabini Rugi Shizaicho” written on 11th February in the 19th year of Tenpyo era (747AD) says that there was a copper workshop in Daianji temple. The sentences concerning the copper workshop are shown below[5)].

合水銀貳佰拾壹斤伍兩
合水鐳壹阡玖佰貳拾壹斤伍兩$_{小}$　肆拾斤陸兩$_{大}$
合銅伍萬貳阡参佰陸拾貳斤$_{小}$　(割注省略)
合鉄壹佰伍拾陸廷

In the text, several notes were also added on copper as below.

生銅五万一千六十二斤
錬銅五百九十斤

熟銅三百廿七斤
悪荒銅三百八十三斤

These notes suggests that copper was divided into several types; Seido, Rendo, Jyukudo and Akuarado. The meaning of these terms is still unclear. Since this paper does not intend to clarify their meaning, the author introduces my opinion only on Akuarado here. As far as the author knows, the term Akuarado first appeared in the 9th century. It is likely that Akuarado is not refined copper but fragments of unfinished copper objects and failed products obtained during copper production.

Temples other than Daianji temple left similar records. For example, Horyuji temple left the text of “Horyuji Garan Engi Narabini Rugi Sizaicho”. The text was written on 11th February in the 19th year of Tenpyo era (747AD).

合水錫壹阡漆佰玖拾壹兩参分
合白鑞壹佰壹斤捌兩
合黒鑞伍拾壹斤

In the Tenpyo era. Horyuji was regarded as a non-state small temple in the law of “Taijinosei” because this temple is far from the capital and small in size. However even this small temple owned copper workshops.

Although copper workshops have not been discovered yet in Daianji temple and Horyuji temple, clay tuyeres discovered in these temples strongly suggest that the temples undoubtedly had copper workshops inside[6].

Todaiji temple also had workshops to produce small copper objects along with workshops for the casting of the Great Buddha statue. The text of “Zoutoudaijishi Chokai”, which is stored at Shosoin, shows that the office for the construction of Todaiji temple called “Zotoudaijishi” owned copper workshops. Other documents stored at Shosoin also show that Todaiji temple owned wood workshops, roof tile workshops, copper workshops, painting workshops and workshops for the casting of the Great Buddha statue.

Officials in the copper workshop included Jyo, Sakan, Sisho and Shoryo. Under these officials, craft specialists such as Zatsuko, Shitei and Koko worked. Other metal smiths probably worked and produced copper wires at other offices such as “Zousekizanjisho” and “Zoukozenyakushijisho”, which belonged to the office of Zoutoudaijishi.

As mentioned above, offices for the construction of Buddhist temples such as Zoutoudaijishi produced necessary materials by themselves. It is likely that theses offices could easily adjust to changing demands. This system probably had a great impact on developments of craft industries in Japan.

### *3) Conclusions: Copper Objects in Buddhist Temples and Shinto Shrines*

In the ancient Japanese law system called “Ritsuryo”, Sinto was regarded as the state religion. This is clearly reflected in the administrative system called “Nikanhassho”. In the system of Nikanhassho, Department of Shinto Affairs called “Jingi-kan” preceded Department of State called “Daijo-kan”. Meanwhile, according to Ritsuryo, Buddhist temples were supervised by the office called “Genba-ryo”. However, in fact, the imperial court spent larger expenditures on Buddisht temples rather than shrines. Buddhist temples were actually managed by special offices called “Reigai-kan”, which were undefined in the law system of Ritsuryo.

Jingu (usually called Ise Jingu) was the main shrine for the state ceremonies. Ritual reconstruction of the shrine (this ceremony was called “Shikinen Sengu”) was performed every 20 years. Except woods, roof thatch, stones and coating materials, every necessary material was produced in the imperial court and transported to Ise. Therefore Jingu in Ise had no copper workshops. The text of “Toyukegugishiki-cho” and the text of “Kotaijingugishiki-cho”, which is designated as a national important cultural property, clearly show that ritual objects and decorations were produced in the imperial court. Both of the texts were written in February, 804.

Formal letters issued by Department of State called “Okurikanpu” from various periods also show that the necessary materials for Shikinen Sengu were produced in the imperial court. In addition, ritual objects used in Sinto were mostly made of woods and rarely decorated with flowers and artificial flowers. As a result, copper objects have been rarely used in shrines. Although white porcelains and white pottery are used as sacred jars containing Sake in modern shrines, wooden jars were originally used in the pre-modern period. Copper objects have not been used in rituals in shrines since the ancient times until now.

Since Shinto and Buddhism gradually molded into one syncretic belief after the end of the ancient times, copper objects was used in its rituals. However after Shinto separated from the Buddhism in the Meiji era, copper objects has been rarely used in Shinto rituals.

Meanwhile copper objects have been valued in Buddhism. Large temples in the capital owned copper workshops and workshops produced amounts of copper objects. Local temples were gradually influenced by the central temples. After the introduction of Tantric Buddhism into Japan by Kukai and Saccho, copper objects became more valued in temples because Tantric Buddhism ritual objects used in Tang China was exclusively made of copper.

In the Ming era, copper objects imitating ancient copper objects became popular in China. These objects were soon introduced into Japanese temples. Buddhist temples in Japan still store old copper objects from the ancient periods while shrines dose not store any copper objects.

In the Kohun Period, copper vessels made of copper-tin-lead alloy were first introduced into Japan. This tradition was inherited by Buddhist temples in Asuka, Nara, and Heian periods. Buddhist temples began to own copper workshops and produced amounts of copper vessels.

Copper vessels stored at Shosoin were used in Buddhist temples rather than in imperial palaces. Therefore some of the vessels have been kept unused. The vessels were left at Shosoin not because they were precious objects imported from the Korean Peninsula but because more objects were imported than those used by participants in rituals. In Korea, copper vessels became serving vessels in the daily life while copper vessels were exclusively used in Buddhist temples in Japan. This is one of the differences in historical developments between Korea and Japan.

***Notes***

1. Toshihiko Morimitsu 毛利光敏彦 1978「古墳出土銅鋺の系譜 (The Origins of Copper Bowls from Kofun Burial Mounds)」『考古学報誌 (Koukogaku Gaihou)』64-1
   Nara National Research Institute for Cultural Properties 奈良文化財研究所 2005『古代東アジアの金属製容器II (Metal Vessels in Ancient East Asia II)』奈良文化財研究所史料 (Nara Bunkazai Kenkyuzyo Siryo)71 冊 . Recent studies by Toshihiko Morimitsu were published in this monograph.
2. Gunma Archaeological Research Foundation 群馬県埋蔵文化財調査団 1999『綿貫観音山古墳 II (Excavations at the Burial Mound of Kannonyama, Watanuki II)』
3. Shosoin (ed) 正倉院事務所編 1994『正倉院宝物 I：北倉 I (Treasures of Shosoin I: Northern Storehouse I)』毎日新聞社 (Mainichi Newspapers). Please refer to pp. 240 to 262.
4. See Nara National Research Institute for Cultural Properties (2005) introduced in Note 1.
5. The sentences are quoted from Rizou Takeuchi 竹内理三『寧楽遺文 (Naraibun)』中巻 (Second Volume) 東京堂 (Tokyo-do)
6. The composition of copper alloys varied to a degree, which supports this idea. As for the analysis data, refer to the following references. As for copper objects stored at Horyuji temple, 179 data are listed in the paper by Takashi Murakami (村上隆),「材質と構造の歴史的変遷 (Historical Developments of Materials and Structures)」, which is included in Nara National Research Institute for Cultural Properties (2005). As for Horyuji treasures dedicated to the imperial family, refer to Tokyo National Museum 東京国立博物館 2004『法隆寺献納宝物特別調査報 供養具 1 (A Report on Horyuji Treasures: Ritual Objects 1)』and Tokyo National Museum 東京国立博物館 2005『法隆寺献納宝物特別調査報 供養具 2 (A Report on Horyuji Treasures: Ritual Objects 2)』. As for copper objects stored at Shosoin, refer to『正倉院年報 (Shosoin Nenpou)』.

# Comparisons of the manufacturing technology of high-tin bronze tools in modern Asia

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### *1. Introduction*

Bronze tools have been manufactured in various areas since the ancient times. Among them is a group of characteristic high-tin bronze artifacts. Because high content of tin makes bronze harder and its color silver-white, high-tin bronze was used to manufacture weapons and mirrors. If content of tin is more than 20%, bronze becomes too hard and fragile. Bronze containing 30% tin is so hard that it can be easily broken just like glass. Bronze containing 40-50% tin is slightly softer and easy to scrape although it may sometimes crack in a mold through solidification shrinkage when it is cast. Bronze containing 50-60% tin is much softer and easier to scrape, and more fragile in a solidification process. Bronze containing 70-80% tin is extremely soft and that containing 80% tin is so soft and sticky that it may not get cracked in casting. Silver-white color appears when bronze contains more than 30% tin and the color does not change among the bronze containing more than 30% tin.

To improve brittleness of high-tin bronze, it is heated until it turns red and then rapidly cooled in water. After this process, its silver-white color turns to yellow-orange to its inner part and looks like as if low-tin bronze. Thus the amount of tin in bronze cannot be identified by color. This process does not decrease the hardness of high-tin bronze, which hardly bend too much by hammering with an iron tool.

Bronze artifacts are usually manufactured by casting. In addition, forging, in which bronze is heated until it turns red (hot forging), can also be used to manufacture high-tin bronze tools. Even a thin sheet of high-tin bronze is so hard that it is difficult to bend after hardening. High-tin bronze cups manufactured by hot forging at workshops in modern India are often only 0.5mm thick and some parts of these cups are as thin as 0.2mm. A thin rim of some bowls gives it resiliency which allows the bowl to be distorted to an oval plan when pressed by hands from the both sides of it and to get back to the original circular shape when released. A reconstructive experiment has demonstrated that a high-tin bronze bowl containing 15% tin, manufactured without a hardening process, can be scraped as thin as to about 0.3mm using a lathe[1)]. It is believed that fragile high-tin bronze containing more than 20% tin can also be scraped by a lathe to similar thickness when it is hardened. When the surface of high-tin bronze tools manufactured by forging is polished in order to erase traces of hammering, its manufacturing method cannot be visually distinguished from that of casting. However, bowls with a ring base or lids with a knob, which is attached neither by riveting, soldering or brazing, can be regarded as being manufactured by casting. Metallographic observation definitely can clarify whether it was cast or forged and provide more detailed information of manufacturing technology.

The manufacturing technology of the particular group of high-tin bronze tools can be investigated by using several different methods, 1) archaeological study of artefacts, 2) analysis of their chemical composition and metallographic observation, 3) investigation of manufacturing technology of modern high-tin bronze objects as well as their metallographic observation, and 4) reconstructive experiment. Internationally cooperative studies allow us to approach the emergence, diffusion, adoption and change of the manufacture method of high-tin bronze tools.

This paper reports the results of my own investigation of modern workshops of high-tin bronze tools, the video footages recently recorded by other investigators, and the descriptions of manufacturing methods of high-tin bronze artifacts in excavation reports, in order to assemble basic references to the study of the ancient manufacturing technology of high-tin bronze tools. The investigation of high-tin bronze in the area west of India has yet to be carried out.

### *2. South Korea*

In South Korea there are workshops and factories which manufacture brass ware made of high-tin bronze contains 22% tin and 78% copper. As brass ware is used for table ware, such as bowls, spoons and chop sticks, gongs (they are in the shape of a circular dish with a vertical wall without having a hemispherical knob called “navel” in the middle of a banging face), religious devices, etc. Eight workshops and factories of brass ware in South Korea were investigated in September 2007, February 2008 and August 2008. Five technological methods were: (1) one workshop using both hot forging and hot Gung Gurum Ock Sikgi technique together, (2) three factories using casting, (3) two factories using hot forging, casting and hot spinning together, (4) one factory using casting, hot spinning and hot press together, and (5) one factory using both hot press and hot spinning together. Although these pyrotechnologies in South Korea have already been reported somewhere else[2)], they can be summarized here as follows. At every workshop/factory, hardening is carried out by craftsmen who are in charge of either casting, forging or processing of bronze using machines while they are carrying out their own task. Every workshop has a lathe for polishing. The number of craftsmen at each workshop/factory is two to four for casting, one to four for spinning, one to four for pressing and two to four for using a lathe, except for the workshop in the case of (1) which has only one craftsman. There are also craftsmen specialized for polishing of the products, such as spoons, which are difficult to polish with a lathe. For the forging in the case of (3), one workshop has two craftsmen and another has three or four craftsmen, who are engaged in hammering (the latter case was only assumed from photographs). While the same craftsmen can sometimes be in charge of both spinning and machine pressing, the craftsmen in charge of casting and those using a lathe are only engaged in their own task.

In modern manufacture of brass ware, casting is carried out using an unbaked mold which is made of two iron frames. This method used in modern mass-production is unsuitable for the manufacture of complex-shaped brass products. Ancient high-tin bronze tools seem to have been manufactured using a baked sand mold. Otherwise, products in a simple form were likely to have been shaped by hot forging after being cast in a stone mold. The emergence of modern unbaked molds has facilitated the production of cast brass ware in a large amount because this method does not require a process to bake molds. Therefore, the production of forged brass ware, which requires a lot of time, necessarily declined and thin brass ware has disappeared in modern products. In fact, cast brass ware can become very thin by scraping it with a lathe. However, to raise productivity, electric lathes were only used for finishing the surface but not for scraping the ware to make it thinner by taking longer time. Gung Gurum Ock Sikgi technique was used in the manufacture of forged brass bowls in order to make it wider at its body than at its rim without taking much time, by extending out the part below the rim from the inside. Nevertheless, this method declined due to the invention of a new casting method using unbaked molds, in which an inner core is inserted in a model of a copper bowl that is divided to an upper and lower part. This method made possible the casting of brass bowls which are narrower at the rim and thus replaced Gung Gurum Ock Sikgi technique. Thus, at the present, most of brass ware, such as bowls and spoons, is manufactured by casting using unbaked molds and thus thick. Today, only gongs are made by hot casting and hardening together with final tuning by cold forging because their manufacture by casting makes its sound poor.

***3. India***

Six workshops in Kerala, which produce bowls, musical instruments, mirrors, and so on, were investigated in February and September in 2009. Five types can be distinguished in the technology used and the type of objects produced: (1) two workshops of mirrors which are cast using a pair of molds, (2) one workshop of bells and basins manufactured by lost-wax casting, (3) one workshop of jugs and vessels by lost-wax casting and also by forging for the latter, (4) one workshop of bowls, table ware, and music instruments by hot forging, and (5) one workshop of music instruments by hot forging. Mirrors produced at the workshops of type (1) are made of high-tin bronze containing 32.6% tin[3)] and manufactured by casting without heat treatment. The workshop of type (2) manufactures bells containing about 10% or more tin and basins made of brass, without using heat treatment for either of them. Jugs and other objects manufactured at the workshop of type (3) contain about 10% or more (13-15%?) tin and manufactured by casting. Forged vessels are made of sheet copper which is connected by brazing. At the workshops of types (4) and (5), high-tin bronze consisting of 21-22% tin and 78-79% copper is cast to the shape of discs or the archetypes of spoons which are about 1cm in thickness and 12 to 15cm in diameter and then finally shaped by hot forging. After their hardening, cold forging is additionally carried out several times for the final shaping of bowls or for the tuning of music instruments.

There are small electric tools such as hand grinder at the workshops of types (2) and (3), and they are used for the surface treatment by polishing. There are both electric and hand lathes at the workshop of type (3). At the workshops of types (4) and (5), final manufacturing procedure is scraping with a hand tool (scraper) after hardening. This is not to erase the traces of hammering but to make its surface glossy by scraping. Bowls or disc gongs (the latter are about 18cm in diameter and 5mm in thickness and used by hanging them with a code put through two holes at their edges in order to bang with a wooden stick) are decorated by scraping their surface in various directions in order to have different reflections of light. At the workshop (3), a hand lathe is spun by pulling in turn an either end of a rope that is rolled on a cylindrical bar. Turning direction changes as the one of two ends of the rope is pulled by either a right or left hand. Turning distance can be controlled by pulling the rope to different length and thus turning direction can be changed before a long spout of a jug. A bronze tool is attached at its base to the end of the cylindrical bar using wax (or resin) and it is scraped with a steel scraper. Two workers are engaged in this work, one for turning and the other for scraping. This paper mentions the workshops of the types (4) and (5), which conduct heat treatment, in detail.

**1) APPUNI (KALADIPARAMBIL CHERUKUDANGAD P.O PALLIPURAM, PATTAMBI, KERALA, INDIA)**

Products in this workshop are bowls, large spoons, disc gongs, cymbals (a pair of slightly curved discs measuring about 18cm in diameter and 5mm in thickness. The center of each disc, which is about 6cm in diameter, bulges and is perforated in the middle. Cords put through these holes are functioned as handles in order to strike each other to make a sound), and so on. At the time of my investigation there are a workshop owner named APPUNI (a presumed age is late 50s) and his three relatives in the workshop. They said that the relatives were called for in order to help my investigation. Although an old worker, who seems to be a father of the owner, was also there, he had already retired from this task because he was too old to conduct daily work. Perhaps this workshop is not operated everyday and thus some failures were observed in their products, for example cracks which occurred during hammering out a bulge of cymbals or occurred during hot forging of bowls. The workshop is located under a tree shade in a forest and is built with pillars standing on an earthen platform and with a roof. It has a wall only in the position which faces the directions of wind (Prefatory Photo 1).

The manufacture process of shallow bowls at this workshop is as follows. (1) Old copper bowls are smashed with an iron hammer and then put into a melting pot of 8kg capacity and heated with charcoal to make high-tin bronze containing about 22% tin. (2) A hollow depression, about 13cm in diameter and 1.5cm in depth, is made in a sand mold using various-sized circular clay stamps (the mold is made of wet coarse sand including little clay. Its color is black because it includes charcoal). The sand mold is neither dried nor baked. (3) Powder of cereal grains is sprayed to the hollow which is then pressed by a stamp again. Molten high-tin bronze is poured into the hollow (Prefatory Photo 3). (4) A disc about 1cm thick is removed from the mold (thickness of the discs is not even at this point). (5) An air vent of the furnace is made by digging a hole about 5cm in diameter and by placing two iron bars about 7mm in thickness (the hole goes down about 10cm deep and then bends at 90 degree and goes horizontally about 1m to a hand bellow which is made of cow skin). (6) Air is sent through a heap of burning charcoal bits placed on the mouth of the air vent, and (7) Four discs are placed in the furnace at once and covered with charcoal bits which is gathered with a wet hand-bloom. (8) A pile of two discs is picked up with iron tongs held in a left hand and turned with a right hand using an iron crook with a L-shaped end until the discs are evenly heated. (9) The workshop owner places a pile of two discs on a concaved stone anvil using tongs held by both hands. He turns the discs and three other workers hammer them to an incurved shape using iron hammers at the pace of about 80 times within 50 seconds (hammering may be finished at various timing, for example when the discs are still in red color, at the moment their red color is disappearing or after their red color completely disappeared). The hammering starts at the part near the edge of the disc and moves circularly, gradually going towards the center of the disc. This is because the edge cools sooner than the center. A process of hammering from the edge to the center is repeated, except for the case in which the center is cooled too quickly and thus not hammered (Prefatory Photo 6). (10) One of the heated discs is placed on a stone anvil and hammered again at the pace of about 80 times within 50 seconds. (11) Another pile of two discs is heated and forged in the same way. (12) A pile of two discs is forged again for 50 seconds. Then, a pile of three discs is forged for 60 seconds and it is repeated three times. Then, a pile of four discs is forged once for 60 seconds. (13) A pile of all six discs are placed on the furnace in order to heat them by turning them upside down (it does not matter if charcoals are accidentally inserted between the discs). (14) The pile of six discs is hammered at the pace of about 100 times within 60 seconds in order to shape them (hammering at the central part stops when it is still red. Piling up six discs prevents them from cooling too quickly and makes it possible to forge them for a longer time even when the discs became thin. It also gives them a standardized thickness and thus allows mass-production). The workshop owner turns a pile of six discs using short tongs in a seated position (Prefatory Photo 7). After that, the pile of six discs is repeatedly forged three times in the same way. (15) The workshop owner stands up and turns the pile of six discs with long tongs (the angle of the pile of bowls becomes nearly vertical and their sides can be hammered more easily) and repeats this seven times. At the beginning, the discs are heated at higher temperature and enlarged remarkably. In the later half of this process, only short-time forging, about 30 seconds, is repeated about 60 times because as the discs become thinner it is easy to melt at high-temperature heating and cool sooner. (16) The pile of six bowls is heated at lower temperature which does not show a red tinge. The workshop owner in a crouching position holds the pile of six bowls with short tongs and forges it by hammering the base of the bowls on his own for 20 seconds and repeats this twice (until this stage, the same stone anvil is used) (Prefatory Photo 8). (17) The pile of six shallow bowls is separated to each that has become about 30cm in diameter. (18) A pile of two of these discs is heated at low temperature and placed obliquely against an iron stand. The discs are made to even thickness by beating their sides from the inside using a broad iron hammer. Bowls without any carination are formed. (19) Each bowl is heated gradually. When its whole surface becomes a red, the bowl is held upside down with tongs and is quenched swiftly in water for hardening (water seems to be ordinary one. It is dirty and stored in a fixed tank). Three bowls without carination are hardened in total. (20) After hammering their sides on an iron anvil, a pile of two bowls are heated and hammered on a stone anvil which is carved in the form of the base and the side of a bowl. The inside of the bowls is hammered with a wooden hammer to form carination of the base and the side (there are two other stone anvils with different shapes) (Prefatory Photo 9). (21) These bowls are heated at the temperature apparently lower than the case in which the bowls without carination are heated (some parts does not even show a red tinge), and they are carried swiftly to a water tank. The bowls are dipped into the water with their bottom upwards for hardening (the color of each bowl tells that hardening temperature is not precisely controlled. While the bowls are always dropped with their bottom upwards the angle to drop them into water varies). In total, three carinated bowls are hardened (Prefatory Photo 10). (22) After hardening, cold forging is carried out using an iron anvil and a hammer to make their thickness even (Prefatory Photo 11). (23) At this point their rims are still wavy, so they are made smooth by cutting them using a steel chisel and a hammer and by rasping them. (24) Only the inside of the bowls is scraped with a hand cutter made of steel with a wooden handle. The edge of the hand cutter is not sharpened with a whetstone but is abraded by moving it within a groove filled with silt, which is carved in a wooden board at the same width as the edge.

Spoons are large, measuring about 50cm long, and seem to be used for cooking and serving foods from pots. As in the case of the discs, high-tin bronze containing about 22% tin is cast into a depressed mold to make their rough form which is 1cm thick. First, a handle is hot-forged and hardened and then a bowl is spread and shaped by hot forging. Finally, the whole spoon is heated and quenched in water for hardening by dipping it horizontally (a heated spoon is placed on the mouth of a water tank horizontally and dropped into the water by pushing it with two sticks) and is taken out of the water and immediately cold forged in order to repair skewness of the handle and make the thickness of the bowl even. The edge of the bowl is sharpened with a rasp and the surface of the bowl is polished with a steel hand-tool to finish.

The methods of forging disc gongs and cymbals and their chemical composition are virtually the same as those of the bowls. Central bulges of cymbals are formed by hammering them from the inside on a depressed stone anvil using a wooden pole with a rounded end. Rope holes are perforated by punching with a pointed nail-like iron when the cymbals are still hot. The disc gong is quenched in water in a vertical position for hardening. After that, two holes are pierced with a hand drill and a rope is put through them to hang the gong. The positions of these holes are decided as the sound of the gong is examined (Prefatory Photo 12). They are 5mm thick and because they are thicker than the bowls they are held with tongs while being quenched and dipped into water more slowly than when quenching the bowls.

**2) ALA FORGE：K.R.SUKU (KOPARAMPATHU KADAVALOOR P.O TRISSUR DIST., KEPALA, INDIA)**

The products in this workshop seem to be mainly musical instruments such as disc gongs and cymbals. Four brothers operate it and the age of the eldest is presumed to be early 40s. The workshop, which is closed by walls on three sides, is a bit small but functional. Manufacturing of disc gongs was documented here. The conduct of each task was swift and precise and seems to have been accustomed through their daily manufacturing.

The manufacturing process of the disc gongs is described below. (1) Mold sand (wet black sand including little clay) is heaped directly on an earthen floor, in a form of a disc with about 35cm in diameter and 6cm in height. Then the sand is depressed with a clay stamp to make a hollow measuring about 13cm in diameter and 1cm in depth, and grain powder is splayed to the hollow. (2) High-tin bronze (22% tin and 78% copper)[4], which shows silver-white color in its section, is melted in a melting pot with 6kg capacity using charcoal heat and then poured to the mold. (3) After one minute, it is removed from the mold and immediately hammered around near the edge of the disc which is placed on a stone anvil, using a rounded iron bar which does not have a handle and is about 5cm in diameter and 20cm in length. Then, the disc is stood against a stone anvil and hammered around its side (these processes are conducted for 40 seconds) (Prefatory Photo 23). (4) Two discs with their rims already hammered are heated together in a furnace using sliced charcoal bits (the eldest brother treats charcoal with a wet hand-broom as he turns the discs. The second eldest brother nearby the first also treats the charcoal with a wet hand-broom and an iron bar with a crooked end as he sends air with a hand-powered blower. The structure of the furnace is the same as that at APPUNI workshop) (Prefatory Photo 24). (5) The discs are heated in the furnace for 40 seconds. Then, one of them is placed on a stone anvil and hammered for 40 seconds at the positions previously hammered after its molding. Another disc is hammered in the same way. (6) A person controlling a blower is replaced by the fourth brother, and the second and the third brothers hammer now. The first brother turns the disc with tongs held in both of his hands, and the disc is hammered around the part near the edge in order not to make the edge too thin by hammering itself (Prefatory Photo 26). Then the whole disc is hammered in a spiral direction towards its center. Hammering is conducted at the pace of about 47 times within 20 seconds to finish one disc. (7) The similar process is carried out again, although the tempo of hammering is now about 60 times within 24 seconds. (8) A person controlling a blower is replaced by the second brother, and only the third brother hammers around the edge 43 times within 20 seconds. It is hammered at the position where a half of the hammering face of the hammer hits out of the disc edge. (9) Only the third brother hammers in a spiral direction 40 times within 20 seconds from near the edge towards the center. It is hammered more weakly than when hammered by two persons. (10) The third brother hammers around the edge for 20 seconds on his own, in a way in which the half of the hammering face of the hammer hits outside the disc edge. This process is repeated twice. The thickness of the disc becomes about 5 mm in this process (a stone anvil is always employed until this process, and two discs are both processed in the same way. Hammering is applied only on the one face and the other face is never hammered). (11) The third brother places a disc on a slightly depressed wooden anvil and turns the disc. The first brother hammers around the part near the edge using a rounded iron bar previously used. It seems to modulate bulges. (12) Standing the disc vertically on another wooden anvil, the first brother hammers around its side in a short pitch using a small iron hammer with a handle while the third brother turns it (Prefatory Photo 27). This process is repeated three times. (13) While the first brother turns it on the stone anvil, the third brother hammers on the raised face, which has not been hammered, in order to make it nearly flat (leaving it slightly raised) using a wooden hammer with a hammering face measuring about 8cm in diameter. Hammering is done about 60 times within 20 seconds and this is repeated twice (all hammering is hot forging until this process). (14) Heating the disc until it evenly turns red. The third brother holds it with two tongs, and immerses it vertically into dirty water in a large bucket for hardening. The speed of immersion is neither so swift nor intentionally slow. (15) Because one of these two discs was deformed (skewed) through the hardening process, it was heated, hammered with a wooden hammer and hardened again. But it was still slightly deformed. (16) The disc is cold forged on an iron anvil for two minutes in order to mend its deformation (Prefatory Photo 28). The sound is checked by banging it with a wooden stick. (17) The side of the disc is rasped and a slightly uneven front face is scraped with a steel hand-tool. The traces of scraping look like a decoration motif due to their reflection of light. On its convex reverse face, which is covered with an oxidized layer and represents dark gray, a draft of a flower motif is drawn and then the lines are incised with a steel hand-tool to make liner decorations. (18) After finishing the disc by scraping, the edge of the disc is pinched by fingers and the disc is banged with a wooden stick. While listening to its sound the positions to pierce holes for hanging rope are decided. After drilling holes at these positions, a rope is put through them to finish.

***4. Myanmar***

The manufacturing technology of high-tin bronze tools in Myanmar is described here by referring to the video documents recorded in 2002 by Mr. Masatoyo Miyoshi, a metalworking artist (living in Kita, Osaka) and to his report (a report of the Overseas Study Program for Artists, the Agency Cultural Affairs, 2002)

A manufacturing process of large gongs (they are in the shape of a vertically sided shallow bowl placed upside down and have a hemispherical protrusion called "navel" in the center) is as follows. (1) High-tin bronze (22.2% tin and 77.8% copper) is poured into a clay mold which has a depression measuring a little less than 40cm in diameter and about 2.5cm in depth (the mold is made of clay tempered with chaff and is fired with charcoal after it is dried). The removal of a solidified surface layer, by pinching it with wooden sticks and dragging it out of the mold, removes waste inclusion such as floating charcoal bits. (2) The turner (a worker who turns a disc) heats the disc as he holds it with iron tongs and turns it using an iron bar which has a crooked end, as seen in the workshops in India and South Korea. Air is sent to a charcoal furnace using a two cylindrical bellows standing vertically. To move the disc between the heating furnace and the forging anvil, another worker pulls a rope which is tied with the tongs through a pulley on the ceilings. (3) Standing the disc vertically, it is at first hammered at its side (a thick part). (4) Then, placing the disc horizontally on an iron anvil (it is an iron bar which is about 10cm in diameter and is embedded in the ground. The working face of this anvil is thus circular) it is forged by three hammering workers sitting on a chair in the opposite side of the turner. (5) Because the disc is too large for the turner, who holds it with tongs, to fix the angle between the disc and the iron anvil, the disc is placed on two clay mounds built at the turner's side of the anvil in order to lift it and fix the angle. The gong is shaped while the location and the height of the clay mounds are changed. The turner's tongs holding the center of the disc is positioned between these two clay mounds which are about 25cm apart. (6) The first forging is about 45 times within 30 seconds. While turning the disc, hammering starts from its central part. Because the distance that is hammered in a circle is not so large, the forging finishes when the disc is still in a reddish tone. (7) In the second forging, the position outside the central part of the disc is hammered and then hammering positions gradually move towards its edge. Thus, the clay mounds are moved far from the iron anvil towards the turner and are raised. Forging is conducted for about 30 seconds in one turn. As the distance of hammering in a circle becomes longer, it is hammered about 70 times in one turn. By bending the edge of the disc, the side of the gong is almost formed. (8) An iron plate is stood on the near half of the iron anvil and the edge of the gong is placed at the right angle in the corner between the iron plate and the anvil. To make a sharp carination between the bottom and the side of the gong which is shaped like a shallow bowl, the inside of the gong is beaten with a wooden hammer which has an acute-angled head (Photo 1). (9) The gong is placed on its back on a large wooden board with a hole about 20cm in diameter and a "navel" (protrusion) is hammered out at its center by beating it from the inside using a wooden hammer or a round-ended wooden stick. Simultaneously, two hammering workers make its bottom even with wooden hammers (all hammerings are hot forging until this process). It becomes a large gong measuring about 80cm in diameter. (10) It is evenly heated while holding it upside down and turning it in a furnace. To judge the temperature suitable for hardening, the color of bronze is observed by frequently wiping off charcoal powder lying on its surface using a cloth attached at the end of a stick. The gong is carried from the furnace to a water tank in five seconds and quenched in water, holding its bottom upwards, for hardening (Photo 2). (11) To make it sound better, it is formed by cold forging. The both faces are hammered. While hammering it is pressed down with a wooden stick in order to decrease hammering vibrations or is placed on an iron anvil. After drilling two holes to put a rope, it is finished.

For the manufacturing of a spoon about 17cm long, firstly high-tin bronze (ratio of tin is unknown) is poured to a deep hollow in an oiled stone mold. When it is cast the bowl of the spoon is not flat. After eight seconds, when it is still very hot, the first forging is carried out on an iron anvil (a column embedded in a ground with its top emerging above the ground to 6-10cm and measuring about 13cm in diameter. Its working face is not flat but is slightly convex) for 20 seconds using an iron hammer. At first its handle is vertically flattened in order to make it easy to hold with tongs and then the bowl is spread. By heating with charcoal, further forging makes the handle horizontally flat again. Forging is conducted for a pile of six spoons at once. By forging them together the spoons are not cooled very quickly and it is possible to forge them for a longer time. This is also suitable for forging them to the same form in a short time. The bowl is hammered within a depressed wooden anvil using a round-headed iron hammer in order to make its curvature even. All of these processes are hot forging. After hardening, it is scraped, polished and then finished.

For the production of small bowls, a high-tin bronze disc measuring 5cm in diameter and 1cm in thickness is cast and the first forging is carried out on an iron anvil while it is still very hot. After hammering the disc hard around its center in order to spread and thin the disc, the disc is placed vertically and its side is hammered around to prevent its edge from spreading and cracking. Then, it is hammered in a circle from its center towards its edge. Four bowls are piled together and they are hammered in circle to spread from the center to the edge again to the dimension of 9cm in diameter. As it is hammered one round it is heated again every time. This process of hammering from the center to the edge is repeated. And, the inside of the pile of the bowls is hammered on a depressed wooden anvil using a round-headed wooden hammer in order to round the angle between the bottom and the side. After dividing it to each bowl, the side of each bowl is hammered in the same way, using a wooden hammer, to make its thickness even. All of these processes are hot forging so far, and bowls with a rounded base, measuring 12cm in diameter at the rim and 6cm in height, are formed. After hardening, the rim and other parts are made fine circle by cold forging on an iron anvil using an iron hammer. After that, scraping is carried out.

A scraping lathe is turned in the same manner as the hand lathe in India. One end of a rope which is tied to a spindle shaft is bound to a foot pedal and the other end is bound to the end of a bamboo stick. Stepping on the pedal by a left foot makes the lathe turn in one direction and loosening the pedal makes it turn in a reverse direction because the rope is pulled by the bamboo stick which functions as a spring. The bamboo is repeatedly bent like a fishing rod. By putting a bronze bowl on the turning shaft with wax, it is scraped with a steel scraper.

### *5. Indonesia*

A manufacturing technology of high-tin bronze tools in Indonesia is introduced here, referring to the video footage documented by Masatoyo Miyoshi again.

The manufacturing process of large gongs (in a shape of a shallow bowl placed upside down and have a hemispherical protrusion called “navel” in the center) is as follows. (1) A disc made of high-tin bronze (ratio of tin is unknown) measuring about 40cm in diameter and 2cm in thickness is cast in a mold which has a circular hollow. After heating, the disc is placed vertically and its side is hammered with an iron hammer. (2) The disc is placed on a charcoal furnace to which air is sent by an electric blower and is turned in one direction to another using two iron sticks. (3) The disc is placed on an iron anvil embedded in the ground (its working face is flat and about 30cm by 10cm) and hot forging is carried out by four standing workers. The angle of the disc to the iron anvil is determined by the height of a clay mound. The clay mound is placed at the left side of a turner, and hammering workers locate themselves at the opposite side or the right side of the turner. Hammering begins when the surface is brightly red (pinkish) and ends when red color fades out on its surface and faintly remains in its core. (4) The first hammering is 108 times within 45 seconds and 139 times in 54 seconds. The part which is about 10cm inside of the edge is hammered a half round, and then the outer part is hammered a half round to spread the disc outward. After hammering a half round, the direction of hammering is reversed and the hammering does not go beyond the half of the disc. After finishing this half, the other half is hammered in the same way. The hammering pace decreases to about 70 times within 30 seconds because the disc becomes thin and gets cooled more quickly. The position at which previous hammering stopped is marked by a white line drawn by a chalk or something and the next hammering starts from this line. The central part of the disc, about 20cm in diameter, is not hammered and its outer part is only hammered to spread the disc. (5) While being forged with an iron hammer, the disc is also hammered with wooden hammers by two workers. This is not to spread the disc but to shape it (Photo 4). (6) In the second half of the work, forging is repeated from the center to the edge to spread the disc, and the edge is bent and raised (Photo 5). (7) Placing the disc on a hole, which is about 18cm in diameter and located beside the embedded iron anvil, a “navel” is protruded at the center of the disc by beating with an iron hammer. To produce this navel the central part of the disc has been kept thick by not hammering it during the first half of the work. (8) By tuning the disc in the hole, the base of its edge is hammered outwards until the diameter of the gong becomes a desired dimension. Now the disc gong is placed slightly obliquely on a vertical face of an iron anvil and hammered with a wooden hammer from the inside in order to shape its side to the one inclining inward towards a rim. It becomes a large gong measuring 70cm or more in diameter. (9) The gong is heated in a furnace by turning it over several times. When it becomes red, it is placed on its back and an iron ring is put to its edge (to prevent deformation at quenching?). Then it is carried from the furnace to a water tank by two persons using tongs, and after four seconds, it is quenched for hardening. Another person pushes it with a stick to sink it from the back. (10) After hardening, it is cold forged to form. The both faces are hammered, being held with a wooden stick or being set on an iron anvil in order to decrease the vibrations (Photo 6). Setting the gong on an iron stand, the inside of its side is hammered, too. To find a place to strike for tuning its sound, a fist-sized clay lump is put on the both faces of the gong being struck, or the differences of its vibration is examined by faintly touching its surface. Then, it is finished (Photo 7).

### *6. Japan*

Three examples, for which workshops were investigated or the technology is known from published reports, are reported here. Other workshops of high-tin bronze tools in Japan cannot be recognized so far.

The investigation of Koide Cymbals Factory in Hirano, Osaka, is reported below. This factory manufactures cymbals made of high-tin bronze consisting of 20% tin and 80% copper for a dram set used for modern music. Brass cymbals are usually used for practice and this factory manufactures only high-tin bronze cymbals. Toshio Koike, the representative director, began the manufacture of cymbals by learning it on his own around 1998 and it continues until now. High-tin bronze are imported from Turkey. After heating a thin disc in a furnace and hardening it (Photo 8), it is processed by cold spinning. In this process in a cold state, the control of temperature for hardening is important and adequate heating is needed. After spinning, its sound is tuned by cold forging. Percussion instruments made of high-tin bronze have complex characteristics as a musical instrument. For example, the sound of cymbals becomes muffled for a while after spinning or cold forging and the sound becomes poorer after its use for several years. To make the sound of cymbals better it is important to shape an extremely thin large disc, with less than 1mm thick, to a regular shape. Sometimes it gets broken by hard percussion when playing music. Cymbals are manufactured taking care of both sound quality and strength.

The investigation of a Rin'yo Workshop Ltd. in Minami, Kyoto is reported as follows. This workshop manufactures Orin, one of singing bowls for Buddhist altar fittings. According to Katsuaki Shirai, a workshop owner, his genealogy can be traced back to the foundation of the workshop in 1843. The products of this workshop are percussion instruments, such as Orin and singing bowls used as a musical accompaniment at Yamaboko parade of the Gion festival. High-tin bronze consisting of 20% or more tin and 70% or more copper is cast to the shape of Orin (bowl-shaped) by a traditional Manegata casting method (casting in a baked mold which is made of burnt sand and clay). After heating, it is quenched for hardening and scraped with a lathe. After polished, decorations are sometimes incised on its surface with a graver. Finally, it is heated again, and gradually cooled and finished. This heating process is quite important because it influences the quality of its sound. An Orin produced at this workshop makes a sound with a slightly high and long tone due to this heating process (Photo 9).

Iraku Uozumi studied the manufacture technology of gongs around 1937 as he worked in a factory for Buddhist altar fittings in Osaka. He came back to Kanazawa to begin the manufacture of gongs by himself. High-tin bronze consisting of 20.6% tin and 79.4% copper (the ratio of tin to copper is 26 to 100) is cast to the shape of a gong by a lost-wax casting method in which plates of wax is put inside a clay mold that is made by turning a gauge. After polishing, hardening and cold forging are carried out. After that, it is heated again until it turns to dark red and is gradually cooled to finish[5]. It is formed by casting, then hardened, heated and cooled slowly. This method is different from that of forged gongs manufactured in other regions. After the death of Iraku Uozumi in 1964, his successor has manufactured high-tin bronze tools. The gongs produced by Iraku Uozumi have the shape of a circular shallow bowl placed upside down, with a protrusion called a "navel" in its center.

***7. Summary***

In the manufacturing method of high-tin bronze tools by casting, the products are formed by hot forging and then further shaped by cold forging after it is hardened. Cold forging of music instruments after the hardening is carried out in order to tune their sound. The basic process is generally identical between India, Myanmar and Indonesia, although the way in which they are hammered and the angles at which they are quenched in water for hardening are different. Photographs displayed in the Brass Ware Museum in Daegu, South Korea, demonstrate that gongs were manufactured in South Korea until recently in a similar manner to the bowls and spoons manufactured in India and Myanmar, namely hot forging of a pile of gongs. This fact tell us that an extremely similar method of hot forging and hardening was employed in India, Myanmar and South Korea, although the manufacture technology in the continent of China must be compared with them in further studies.

Some copper bowls in the Goryeo and the Joseon periods in South Korea are made of high-tin bronze including 20-21% tin. Metallographic observations suggest that some of them were made by hot forging and hardening[6]. They are thin, about 0.3mm thick. High-tin bronze bowls at the workshop in India have the same thickness, and the manufacture methods of the both are possibly identical. Metallographic observations also show that, among copper bowls containing 20% tin in the Goryeo period, some were manufactured by hardening cast bronze[6]. They have a stand and thus are difficult to make by forging.

The heat treatment of Orin in modern Japan is characteristics and different from the high-tin bronze tools produced in other regions because it is heated and slowly cooled before finishing. The time and place in which this technology was originally developed is still unknown. In any cases, heating and slow cooling make the products more fragile. So this process is probably applied for Orin, which is always rung gently and is expected to make better sound. Gongs produced by Uozumi might have been produced by borrowing the manufacture technique of Orin made of high-tin bronze because there are some similarities in their production. The gongs by Uozumi which were used in a tea room is to be struck more strongly than the Orin made of high-tin bronze, while it is struck more gently than the gongs in South Asia and South Korea. It is thus supposed that the ratio of tin in the Uozumi's gongs is lower than that in Orin in order not to get broken easily.

It has been explained that the gong displayed in the Gallery of Horyuji Treasures, Tokyo National Museum, 35.0cm in diameter, 5.4cm in height and 4mm in thickness, from the Kamakura period[7)], is similar to the gong in South Korea because it lacks a hemispherical protrusion (“navel”) in its center. However, the center of the gong in Tokyo National Museum is slightly depressed while the gong of South Korea has an almost flat surface (a face to be struck). Hammering traces on its whole surface are coarse and leave sharp and deep hammering marks aligned in concentric circles. If this is made of high-tin bronze, such deep traces of hammering are likely to have been produced by hot forging. However, it was hammered on its front face using an iron hammer, by setting its reverse face on an iron anvil and this is different from the gongs in modern South Korea, Myanmar or Indonesia, for which a reverse face is hammered through hot forging. The context of its production will become clear through further studies of the history of the gong manufacturing technology in East Asia.

The gong recently purchased by Fuminori Sugaya in central Vietnam is made of brass consisting of 32% zinc and 68% copper, measuring 31cm in diameter, 4cm in height at its edge and 0.8-1.2mm in thickness[4)] (its form is similar to gongs in Myanmar and Indonesia, where it has a hemispherical protrusion or a “navel” in the center and is particularly similar to those of Indonesia because it has a concave band running in circle around a flat face outside the navel). It has hammering traces on its whole surface and was probably made by cold forging. The concave band was hammered out from its front face. Its detail, for example whether or not the technology of high-tin bronze gongs was applied to produce this brass gong, is yet to be known.

This paper introduced the modern technology used at the workshops of high-tin bronze tools in main regions of Asia from India to the east, except for China. In future Chinese scholars will investigate and provide the information on the modern technology of high-tin bronze tools in China. Furthermore, as the investigation of workshops for high-tin bronze tools in the regions west of India develops, the information on the modern manufacturing technologies of high-tin bronze tools in the whole Asia will be collected. Some elements of the current technology employed in each region might have been diffused in modern times, and the origin and the route of diffusion of ancient technology must be examined carefully from an archaeological viewpoint. The investigations of the modern workshops for high-tin bronze tools containing more than 20% copper enables us to study a history of manufacture technology of high-tin bronze tools since the ancient times in a more practical way. Therefore, I believe that the primary purpose of this paper was accomplished.

***Acknowledgments***

To complete this paper, I would like to express my gratitude to those who were working at surveyed workshops for high-tin bronze tools in India and South Korea and to the following persons for their supports and advices.

Eun-Seok Lee, Srinivasa Ranganathan, R. M. Pillai, Sharada Srinivasan, Vimal Kumar, Masatoyo Miyoshi, Toshio Koide, Katsuaki Shirai, Yasuji Shimizu, Takekazu Nagae, Kimiko Shimazoe, Saho Shibata

***Notes***

1) The copper bowl recovered from Gunma Prefecture was reconstructed by Mr. Nin'ichi Wada, the turner living in Takaoka, Toyama.

2) Takekazu Nagae and Haruhisa Mifune (eds.), Technologies of Heat treatment and manufacturing in Korean Peninsula. Report of Researcher Exchanges Program of JSPS in 2009, (ISBN978-4-9905066-0-5), Faculty of Art and Design, University of Toyama, 2010.

3) Sharada Srinivasan and Ian Glover, Skilled mirror craft of intermetallic delta high-tin bronze ($Cu_{31}Sn_8$,32.6% tin) from Aranmula, Kerala. In: Heat Treatment and Casting Techniques of Asian High-Tin Bronze Wares. Faculty of Art and Design, University of Toyama, pp.3-8, 2008.

4) The result of the X-ray fluorescence analysis on the polished surface of the product by Dr. Takekazu

Nagae (University of Toyama).
5) Hiromichi Kimura, Iraku Uozumi: the manufacturing process of the gong. Shodo Sasaki, In: Kiyoshi Un'no and Iraku Uozumi. Living National Treasures Series 28. Kodansha, 1979.
6) Takekazu Nagae and Sang-Yong Lee, Metallography of high-tin bronze tools in Goryeo and Joseon periods. In: Technologies of Heat treatment and manufacturing in Korean Peninsula. Report of Researcher Exchanges Program of JSPS in 2009, (ISBN978-4-9905066-0-5), Faculty of Art and Design, University of Toyama, pp. 81-93, 194-196, 2010.
7) Treasures Dedicated to Horyuji. Tokyo National Museum, 1975.

Photo 1. Hot forging of the gong in Myanmar. The carination of the bent side is forged from the inside using a wooden hammer. (From the video footage documented by Mr. Masatoyo Miyoshi)

Photo 2. Hardening of the gong in Myanmar. Heated dram is quenched by dipping it from the back into a water tank for hardening. (From the video footage documented by Mr. Masatoyo Miyoshi)

Photo 3. Cold forging of the gong in Myanmar. After hardening, it is hammered as held with a wooden stick. (From the video footage documented by Mr. Masatoyo Miyoshi)

Photo 4. Hot forging of the gong in Indonesia. While forging with an iron hammer, it is formed by beating with an wooden hammer. (From the video footage documented by Mr. Masatoyo Miyoshi)

Photo 5. Hot forging of the gong in Indonesia. The side is high, and the rim is strongly inclined. (From the video footage documented by Mr. Masatoyo Miyoshi)

Photo 6. Cold forging of the gong in Indonesia. After hardening, it is beaten with an iron hammer to form, as held with a wooden stick. (From the video footage documented by Mr. Masatoyo Miyoshi)

Photo 7. The finished gongs in Indonesia. The gongs arranged at the entrance of the workshop. (From the video footage documented by Mr. Masatoyo Miyoshi)

Photo 8. Hardening in Koide Cymbals Factory. A thin disc of high-tin bronze measuring about 1mm thick is hardened and cold-forged.

Photo 9. Orin and a call bell of Rin'yo Workshop. The both are made of high-tin bronze containing 20% or more tin, through heating and slow cooling processes. (Photo by Mr. Katsuaki Shirai)

## Origin and diffusion of binary high-tin bronze wares: introduction of sahari into Japan

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### *I. Introduction*

Treasures of the Shosoin and the Horyuji temple include many high-tin bronze vessels called *sahari*. The name of *sahari* itself introduced into Japan since the Early Modern period, while *hakudo* was used as the name of high-tin bronze wares in antiquity (成瀬 2002). The wares were also named *kyodo* in China, employed to make musical instruments like *dora*s or gongs. In principal, *sahari* consists of lead-free alloys, characterized by two main components of copper (Cu) and tin (Sn). These binary high-tin bronze wares were produced through forging or casting. In addition, thermal treatment technique as a hardening process was often applied to the production. In general, bronze wares in East Asian regions, represented by bronze mirrors in ancient China, consist of leaded high-tin alloys, although small-scale, but earlier use of lead-free high-tin bronze wares was also identified in the regions. On the other hand, the appearance of binary high-tin bronze vessels, which comparable to *sahari* vessels in the collection of the Shosoin, in the East Asian regions has apparently confirmed at relatively later stages of use of the alloys, suggesting established binary high-tin bronze technology was introduced into the East Asian regions including Japan from some other places (清水 2009).

Based on components of alloys, fabrication techniques (forging/casting), and thermal treatment processes, this paper deals with dates and distributions of binary high-tin bronze artifacts recovered from various regions of Asia, in an attempt to investigate origin and diffusion of binary high-tin bronze wares.

### *II. Definition and classification of binary high-tin bronze wares*

#### Definition of binary high-tin bronze wares

First, binary high-tin bronze wares are defined as high-tin alloys called *sahari*, *kyodo*, or *hakudo* in East Asian historical contexts. For example, some *sahari* artifacts in the collections of the Shosoin and the Horyuji temple indicate around 20 % Sn through nondestructive testing (成瀬 2002; 村上 2005). As has been reported by a recent paper (庄田 et al. 2009), modern Korean *yugi* wares also demonstrate similar proportions, i.e., c. 78 % Cu and c. 22% Sn. Metallurgically, binary high-tin bronze wares contain more than 10% Sn in a broad sense and more than 16% Sn in a narrow sense. In addition, binary high-tin bronze wares are further divided into ‘small’ (10% to 16% Sn), ‘medium’ (16% to 25% Sn), and ‘large’ (more than 25% Sn), based on the proportions of Sn contents (長柄 2008). In general, ‘medium’ high-tin bronze wares are applied thermal treatment processes for the purpose of improvement of strength. For this reason, ‘medium’ high-tin bronze wares have been termed as ‘thermally processed’ high-tin bronze wares (長柄 2010). The proportion of 10% to 16% Sn of ‘thermally processed’ high-tin bronze wares is also an appropriate range in order to perform thermal treatment processes. On the other hand, over 25% Sn contents in the alloys disturb the thermal processes for the purpose of improvement of strength, since the processes eliminate the $\alpha$ phase in the matrix. For this reason, strength of ‘large’ high-tin bronze wares might be insufficient to perform thermal treatment. However, ‘thermally processed’ high-tin bronze wares in this paper comprise ‘large’ and ‘middle’ high-tin bronze wares for the convenience of the study.

Second, presence or absence of lead (Pb) in the alloys is pushed forward. Binary high-tin bronze wares are principally lead-free alloys, but the wares represented by bronze mirrors in East Asian regions contain around 5 % Pb in general. Aggregated Pb components in the alloys often develop cracks because of impacts of forging (Craddock et al. 1988), which is the major fabrication technique of binary high-tin bronze wares. Possible provenances of lead in the alloys include intentional admixture, contaminant from ores, and contaminant from re-used bronze wares. For this reason, this paper tentatively defines less than 1% Pb contents as an attribute of binary high-tin bronze wares.

Third, thermal treatment is a significant element of binary high-tin bronze wares. Modern Korean (i.e., *yugi*) and Indian high-tin bronze productions involve thermal treatment techniques for polishing at the final stage of the productions (長柄 et al. 2009). In principal, the thermal processes are required to improve strength of the bronze wares at the points of polishing and practical use, although some high-tin bronze wares with around 22% Sn have been made without the thermal processes.

Last, fabrication techniques of forging and casting should be considered. In East Asia, casting was the major technique of bronze fabrications including high-tin bronze wares in general. On the other hand, in the ancient Near and Middle East, pure copper or high-copper alloys were often fabricated through forging. The major fabrication technique of high-tin bronze wares was also hot forging in general, although minor adjustments after thermal treatment and tuning of percussion instruments represented by *dora*s were performed through cold forging. Some binary high-tin bronze wares were fabricated through casting. Nevertheless, principal fabrication technique of the lead-free high-tin alloys was hot forging, since absence of lead is closely relevant to forging technique.

**Classification criteria for binary high-tin bronze wares**

Based on above-mentioned elements of binary high-tin bronze wares, classification criteria of the artifacts are established. First, S(a) is defined as bronze wares with more than 16% Sn content, while S(b) is under 16% Sn content. The minimum Sn content of S(b) corresponds to the range of ‘small’ high-tin bronze wares. Second, P(a) is defined as bronze wares with under 1% Pb content, while P(b) is more than 1% Pb content. Third, H(a) is defined as bronze wares with thermal treatment like quenching, while H(b) has no thermal treatment. Last, F(a) represents forging, while C(b) represents casting. Attributes represented by (a) in the criteria indicate characteristics of binary high-tin bronze wares. For this reason, bronze wares composed of S(a)+P(a) +H(a) +F(a) corresponds to typical binary high-tin bronze wares. On the other hand, bronze wares composed of S(b) + P(b) + H(b) + C(b) contain no attributes of typical binary high-tin bronze wares.

In the classification system, two attributes of Sn proportions and fabrication techniques are emphasized. As a result, S(a)+F(a), S(a)+C(b), S(b)+F(a) and S(b)+C(b) represent Type A, Type B, Type CA, and Type CB respectively. Based on the rest two attributes of presence or absence of thermal treatment and Pb proportions, these types are further subdivided. In theory, sixteen types (from A1 to CB4) of binary high-tin bronze wares are established in the system (Table 1).

### *III. Dates and distributions of binary high-tin bronze wares in Asia (Figs. 1 and 2)*

The following sections illustrate an overview of binary high-tin bronze wares in various regions in Asia. Attentions will particularly be paid to bronze vessels, since the vessels from the regions possibly contain common characteristics. Because a previous paper by the author (清水 2009) has also surveyed various high-tin bronze artifacts from the regions, only recent information will be reviewed in the followings.

**Japan**

High-tin bronze wares first appeared as leaded alloys in Japan in the Yayoi Period. Those bronze artifacts were apparently imported from the Korean Peninsula. In the Late Yayoi period, high-tin leaded bronze mirrors comparable with Han-style mirrors in China were locally produced in Japan. The proportions of Sn contents of the local mirrors correspond to the range of ‘medium’ high-tin bronze wares (久野 1989).

Possible candidates of the earliest binary high-tin bronze wares appeared in the Late Kofun period (early 6th century AD) in Japan. The bronze wares are mainly composed of bronze vessels like bronze bowls. 113 bronze bowls have thus far been documented (毛利光 1991), but few destructive analyses of the bowls have been conducted. For this reason, the proportions of Sn contents of the bronze bowls have not yet been clearly confirmed. Because no metallographic examinations of the bowls have also been conducted, fabrication techniques (forging or casting) of the bowls remain to be attested. So far, only morphological analyses or observations of hammering traces with naked eyes show the fabrication techniques of the bronze bowls. As a result, typical binary high-tin bronze wares (Type A1) have not yet been attested in the Kofun period.

Further examination of chemical compositions of the bowls has certainly been required, but, recently, some data of the compositions has been published. For example, a sample from the Zaruuchi Ouketsu site in Fukushima prefecture contains 70% Cu, 25% Sn, and 5% Pb. Based on morphological observation, casting technique was apparently employed for fabrication of the sample (押本 2002), assigned to Type B2 or Type B4 of the classification system defined above. A bronze bowl from the Tonoda Kofun site in Okayama prefecture contains 70% Cu, 17% Sn, and 13% Pb (持田 et al. 2010). Because the high proportion of Pb generally disturbs forging technique, the bowl was probably fabricated through casting, assigned to Type B4. A similar bronze bowl from the Kojin Nishi Kofun site in Okayama prefecture contains 83% Cu, 1% Sn, and 16% Pb (持田 et al. 2010). Because of the large proportion of Pb in the contents, casting technique without thermal treatments was possibly employed for fabrication of the bowl. Although bronze bowls are a typical characteristic of binary high-tin bronze wares, the bowl from the Kojin Nishi Kofun site contains no attributes of binary high-tin bronze wares.

On the other hand, *sahari* bronze wares from the collection of the Shosoin, which predominantly consist of bronze wares in the Nara period, include binary high-tin bronze wares, based on the results of nondestructive analyses. Unfortunately, destructive analyses of the well-preserved artifacts have not been performed because of the heritage character of the collection. The results of nondestructive analyses have been published. For example, South Section 46 *Sahari* Plates No. 59 (10 pieces) contains c. 80% Cu and c. 20% Sn with small amounts of Fe, Ni, and Ag (木村 et al. 1989).

*Sahari* wares from the collection of the Horyuji temple also contain binary high-tin bronze wares in the Asuka and later periods. Because of the same reason as the Shosoin case, analyses of the samples have been based on nondestructive ways. The results showed that samples from the sixth to the seventh century AD indicate around 20% Sn contents. On the other hand, samples from the eighth century AD contained decreased Sn with some Pb contents. In the Middle Ages, some samples showed around 10% Pb contents (村上 2005).

No metallographic data of *sahari* bronze wares in the collections of the Shosoin and the Horyuji was obtained, but the collections certainly include forged artifacts like bronze spoons from the Shosoin, based on morphological observations. For example, South Section 45 Bronze Spoons No. 6 (20 pieces) contains c. 80% Cu and c. 20% Sn in general. Among those spoons, 12 pieces had no Pb contents, while 8 pieces contained very small amount of Pb (木村 et al. 1992). Compared with a cast from the Bunhwangsa temple, Gyeongju, North Gyeongsang (국립경주문화재연구소 2006), the bronze spoons from the Shosoin show clear traces of forging technique. For this reason, it is most probable that hot forging and thermal treatment processes were applied to the spoons, although thermal treatments were not clearly confirmed. As a result, the spoons are assigned to Type A1 or Type A3. Because such shape of artifacts as the spoons are required thermal treatment processes for practical uses, A1 is the most probable type of the bronze spoons. Other binary high-tin bronze wares like bronze bowls without lead are possibly assigned to Type B1 or Type B3.

In summary, the earliest bronze vessels that were closely associated with binary high-tin bronze wares in Japan appeared in the Late Kofun period (early 6th century AD), although production of high-tin leaded bronze wares have been conducted in the Yayoi period. Provenances of bronze bowls in the Kofun period have not yet been confirmed except particular types of vessel shapes, but locally produced bowls and imported bowls from the Korean Peninsula apparently exited, based on analyses of lead isotope ratios (馬淵 1994). It is not clear whether hot forging technique or lead-free bronze bowls existed, because only small part of the samples has been analyzed so far. It seems that bronze vessels in the Asuka and Nara periods (7th to 8th century AD) also consist of local and imported artifacts from Silla in the Korean Peninsula, since large number of archaeological finds and stored collections like the Shosoin bronze wares have been discovered. Contrast to the Kofun period, bronze bowls and spoons in the periods certainly contain lead-free bronze wares. In addition, it is worth reminding that the bronze spoons from the Shosoin were possibly fabricated through hot forging technique, although provenances of the spoons have not yet been confirmed.

Developments of binary high-tin bronze musical instruments in Japan have been poorly understood. Introduction of the instruments into Japan would have been later than binary high-tin bronze vessels, since no *dora*s (or gongs) and *dobatsu*s (or cymbals) included in the ancient collection of the Shosoin and the Horyuji temple. A *dora* with the inscription of 'Kencho 8' (1256 AD) probably imported from the Korean Peninsula and a contemporary *dobatsu* have been stored at the Hyakusaiji temple, Higashi-Omi, Shiga prefecture (岡本 1995). East Asian style *dora*s with a protuberance on the center were often used as an instrument of the Japanese tea ceremony. For this reason, the *dora*s might be employed in the Azuchi-Momoyama period or later, when the tea ceremony flourished (岡本1995) .

**Korea**

105 bronze artifacts from the Early Iron Age (3rd to 1st century BC) until 18th century AD in Korea were analyzed (Park et al. 2007). Referring the work, this section summarizes the current status of the study in the Korean Peninsula.

Analyzed bronze objects in the Early Iron Age consist of weapons, tools and mirrors. All of the samples were fabricated through casting, and no quenching methods were observed. A cast bronze mirror from the Wonboongni site (2nd to 1st century BC) in South Chungcheong in the Early Iron Age contains 32% Sn with Pb. The site also produced a dagger with 17% Sn. A spearhead from the Tanbangdon site at Daejeon (3rd to 2nd century BC) contains 22% Sn and 9% Pb.

Samples analyzed by Park and others from the Korean Three Kingdoms period (4th to 7th century AD) consist of four cast and a forged bronze objects. In the Korean Peninsula, a bronze bowl was attested at a tomb in the Lelang commandery of the Eastern Han period. Subsequently, a considerable number of bronze bowls were excavated from tombs in the Korean Three Kingdoms period, such as Geumgwanchong, Cheonmachong, and the Hwangnam Great Tomb in Gyeongju, and the tomb of King Muryeong in Gongju. Anapchi in the Unified Silla Kingdom period also produced bronze bowls (朝鮮総督府 1924; 文化財管理局 1973; 1974; 1985; 1986). Geumgwanchong, Cheonmachong, and the Hwangnam Great Tomb contain forged bronze vessels, although there is no available data of proportions of the contents (毛利光 1978; 이 2000). The Hwangnam Great Tomb produced both of cast and forged copper vessels. Forged vessel consist of more or less pure copper, while cast vessels contains 15% Sn and no quenching are performed, classified the sample into Type CB3 or Type CB4.

In the Unified Silla Kingdom period (7th to 10th century AD), lead-free or binary high-tin bronze wares appeared. The quenched bronze object contains 24% Sn. However, only Sn contents of cast bronze artifacts have been indicated. Those are classified into Type B1. In addition, Type A1 bronze spoons fabricated through forging with quenching have been confirmed. The stone cast of bronze spoon in the Unified Silla Kingdom period was excavated from the Bunhwangsa temple in Gyeongju, but the smooth-shaped bronze spoons suggest that the spoons were forged after casting. Most probably, the bronze objects consist of binary high-tin bronze wares, although proportions of the contents have not yet been clearly confirmed (국립경주문화재연구소 2006).

In the Goryeo period (10th to 14th century AD), both of bronze vessels and spoons are composed of Type A1 binary high-tin bronze wares.

Bronze vessels and spoons in the Joseon period (14th to 18th century AD) principally consist of Type A1 binary high-tin bronze wares fabricated through forging and quenching. Among the bronze vessels, a cast high-tin bronze bowl contains 23% Sn, 4% Pb, and 1% As, assigned to Type B4.

In summary, Type A1 binary high-tin bronze wares that consist of bronze spoons appeared in the Unified Silla Kingdom period, while bronze bowls were fabricated as Type B1. Subsequently, bronze vessels and spoons in the Goryeo period were composed of Type A1 binary high-tin bronze wares. In the Joseon period, Type A1 binary high-tin bronze wares was the main component, but a Type B4 bronze ware was also attested. The fabrication technique of Type B4 is distinctive from the typical binary high-tin bronze technical tradition.

In modern Korea, Type A1 binary high-tin bronze musical instruments with 22% Sn represented by *dora* (or *jing* in Korean) are commonly made. However, it seems that the production have started no earlier than the 10th century AD. No archaeological evidence of the *dora* production has attested in the Unified Silla Kingdom period. Considering the *dora* at the Hyakusaiji temple, Shiga prefecture in Japan, possibly imported from the Korean Peninsula, the *dora* production in Korea might have started in the Goryeo period (岡本 1995).

**China**

A high-tin bronze ware sample with more than 23% Sn has been reported in the Erlitou period (19th to 16th century BC) in China (曲 et al. 1999). Several samples from the second millennium BC sites have also been analyzed. Among them, considerable data was obtained from earrings from the Zhukaigou (around 17th century BC) and Dadianzi (21st to 16th century BC) sites in Inner Mongolia (李et al. 2000;

李 et al. 2003). An earring from Zhukaigou contains 81.3% Cu and 17% Sn, fabricated through hot forging. The sample is classified into Type A1 or Type A3. Two earrings from Dadianzi were analyzed. One hot forged sample contains 81.8% Cu, 15.1% Sn, and 3.1% Pb, assigned to Type CA2 or Type CA4. The other cast sample contains 80.8% Cu and 18.7% Sn, classified into Type B1 or Type B3. Since the second millennium BC, high-tin bronze wares have been continually attested in China regardless presence or absence of lead. However, the earliest binary high-tin bronze boat appeared at the Douwangmiao site in Nanyang, Henan in the Han period (何et al. 2010). The sample contains 79.0% Cu and 18.73% Sn, fabricated through hot forging and thermal treatment. As a result, the bronze vessel is classified into Type A1. High-tin bronze wares have already attested in the Shan period (郝 et al. 2001) and the Erligang period (孫 1998), but both samples were leaded. For this reason, the archaeological discovery at Douwangmiao suggests that technological knowledge of binary high-tin bronze wares were introduced into China no later than the Han period.

Type A1 binary high-tin bronze musical instruments have been confirmed since the Northern Song period (960-1127 AD), including percussion instruments like gongs or cymbals (何et al. 2009). The collection of the Horyuji temple contains a gong of the Southern and Northern Dynasties period (439-589 AD) (香取 1984). Descriptions in the 'Old Book of Tang' (945 AD) suggest techniques of binary high-tin bronze musical instruments were introduced into China from some other places (清水 2009).

**Southeast Asia**

High-tin bronze wares have been found in Southeast Asia, especially in Thailand. Ban don Taphet (4th century BC to 1st century AD) produced 163 bronze vessels (Bellina et al. 2004). Four samples analyzed by Rajpitak (Rajpitak et al. 1979; Srinivasan et al. 1995) contain 20% to 23% Sn without lead. In addition, thermal treatment was performed for the samples, assigned them to Type A1 or Type B1. Pimai (c. 500 AD) (Smith 1973) and Ban Chaing (late 1st millennium BC) (Wheeler et al. 1976) also produced high-tin bronze wares.

Subsequently, production of binary high-tin bronze percussion instruments represented by gongs flourished in Southeast Asia (Goodway et al. 1987). They are including Type A1 binary high-tin bronze wares. However, the origins and developments of the instruments have been poorly understood because of limited information currently available.

**India**

In India, considerable amount of binary high-tin bronze wares have been discovered. For example, the Taxila site (3rd century BC to 1st century AD) produced binary high-tin bronze wares with 21% to 25% Sn. Because no metallographic data was obtained, thermal treatment or fabrication technique have not yet been confirmed (Marshall 1951).

The Nilgiri (middle to late 1st millennium BC) and the Adichanallur (early to middle 1st millennium BC) sites in Tamil Nadu of south India also produced Type A1 binary high-tin bronze vessels, containing around 22% Sn (Ghosh 1990; Srinivasan et al. 1995). Recently, a bronze bowl from the megalithic site of Mahurjhari (c. 800 BC) in Maharashtra was analyzed. 16 % Sn content of the bowl is modest, but it contains typical characters of Type A1 binary high-tin bronze wares (長柄 et al. 2010).

Mohenjo-daro, a site of the Indus Valley Civilization (around 2000 BC), have already attested binary high-tin bronze wares with 22.6% Sn and 0.86 % Pb (Mackay 1938; Srinivasan 1997). Further investigations of the finds should provide new insights for the history of binary high-tin bronze wares.

**Central Asia and the Middle East**

The westernmost archaeological site that produced a binary high-tin bronze vessel is Noruzmahale Tomb A2 (1st century AD), situated in the Dailaman basin, south of the Caspian Sea (江上 et al. 1966). The sample contains 21.38% Sn and c. 1% Pb with obvious hammering traces. Because presence or absence of thermal treatment has not been confirmed, the bowl is classified into Type A2 or Type A4. It seems that binary high-tin bronze bowls with simple hemispherical wall have been attested in the Early Islamic period in Iran. According to (Allan 1979), the simple shape of the bowls is closely associated with hot forging.

In Central Asia, no binary high-tin bronze vessels have thus far been attested. However, thick bronze mirrors with handle have been reported in the region (Ravich 1996). The shape of the mirrors is a common characteristic of binary high-tin bronze wares. Analyzed twenty samples contain more than 20% Sn except one sample. They are also including Type A1 binary high-tin bronze wares.

The dates range from the sixth century BC to the third century AD, but most of the samples date back to BC (Fig. 4).

A cymbal was uncovered from Noruzmahale Tomb A2, associated with the binary high-tin bronze bowl described above. No analysis of elements of the instrument has been conducted.

### *IV. Origin and diffusion of binary high-tin bronze wares (Fig. 5)*

Binary high-tin bronze wares are characterized by over 16% Sn, lead-free, and hot forging. It appears that the high-tin alloys are closely associated with bronze vessels and percussion instruments. In addition, Type A1 binary high-tin bronze wares were also confirmed in the collection of earrings from Zhukaigou in Inner Mongolia. Obtained information on binary high-tin bronze wares was limited as has been descried above. However, data currently available suggests the origin and possible routes of diffusion of the alloys.

A candidate of the earliest binary high-tin bronze wares is a series of earrings from Zhukaigou and Dadianzi in China. A sample (No. 2699-2) from Zhukaigou belongs to Type A1 binary high-tin bronze wares, but the other contemporary four samples contain only 8.3-12.5 % Sn (李 et al. 2000). The results suggest production of high-tin bronze wares have not yet been established in the period. In addition, earrings (M453: 2) from Dadianzi, which contemporary with the Lower Xiajiadian culture, consist of Type CA2 and Type CA4, while finger rings from the site contains Type B1 and Type B3 (李 et al. 2003). Again, two techniques of casting and forging for the production of the high-tin alloys have concurrently occurred. The archaeological evidence suggests that technology of binary high-tin bronze wares have not fully developed at Dadianzi. Furthermore, few bronze vessels that closely associated with binary high-tin bronze wares were occurred in China. The earliest example of Type A1 binary high-tin bronze vessel is the bronze boat at Douwangmiao in Nanyang in the Han period. The temporal gap between Zhukaigou or Dadianzi and Douwangmiao indicates that particular technological tradition developed in those two different periods.

On the other hand, Indian binary high-tin bronze wares appeared in the early first millennium BC. Bronze bowls from Nilgiri and Adichanallur is included in Type A1. In addition, they contain some 22% Sn. Figure 3 (濱住 1972) shows relationship between appropriate Sn proportions and heating temperatures for forging. Top right on the figure is an appropriate range of high temperature hot forging. Bottom left is a range of forging. Shaded area is an inappropriate range for forging. The figure indicates that c. 22% Sn proportion correspond to wide range of temperatures (530-660°C), which allow us to perform hot forging. The wide range of temperatures enables us to forge bronze wares for relatively long time after extraction from kiln. For this reason, Type A1 binary high-tin bronze wares including c. 22% Sn is an accomplished form of the production, suggesting typical binary high-tin bronze ware production was established in India or surrounding areas in the early first millennium BC (清水 2009).

Although binary high-tin bronze wares were discovered in the Dailaman basin, south of the Caspian Sea, no technological traditions of high-tin bronze vessels occurred in regions located west of India. In the western regions, relatively low-tin bronze vessels were made through forging. Nearchus, an officer of Alexander the Great, described Indian high-tin bronze wares with admiration (after Strabo’s *Geographica*), suggesting high-tin bronze vessels have not produced in the regions. A possible reason that binary high-tin bronze vessels flourished in India might be influences from Central Asia, since ancient tin mines have been discovered in Uzbekistan and Tajikistan, represented by the site of Karnab (2nd millennium BC) (Cierny et al. 2003). On the other hand, only a small number of tin mines have been found in India.

In terms of traditions of high-tin bronze alloys in Central Asia, a series of hot forged mirrors with handle from the regions should be considered (Fig. 4). Casting might be a sufficient technique for the mirrors, but the fact that the mirrors were fabricated through forging suggests the regions contain secure traditions of hot forging. Furthermore, discovered ancient tin mines including Karnab are located at the central part of spread of those mirrors. Dates of the mirrors have thus far been later than bronze vessels from India. Yet Type A1 bronze mirrors with handle dated to the sixth century BC implies that Central Asia was a candidate of the origins of binary high-tin bronze wares. Further detailed surveys of various bronze wares in Central Asia are certainly required, since not only the mirrors but also other types of bronze wares might be produced there. However, if binary high-tin bronze wares appeared not earlier than the early first millennium BC in Central Asia, it is most probable that technology of binary high-tin bronze wares was established in India and surroundings. In this case, technological traditions of forged bronze vessels in the west of India and high-tin bronze alloys in Central Asia might be blended in the north of India, where binary high-tin bronze wares would be established. Introduction of horseback riding in India may support this hypothesis. The megalithic site of Mahurjhari produced the earliest Type A1 binary high-tin bronze bowl as mentioned above. The site has also attested early (i.e. early 1st millennium BC) horse harnesses (Deo 1973). The co-appearance of two different bronze objects at the site in the same period suggests that introduction of binary high-tin bronze wares into India might be closely associated with early horse riders in Central Asia.

Subsequently, binary high-tin bronze wares would be introduced into East Asia. The bronze boat uncovered at Douwangmiao in Nanyang suggests that the bronze technology possibly came not later than the Han period from India. It is also possible that the bronze technology was locally developed in China. However, no Type A1 binary high-tin bronze bowls have been discovered in China before the period, suggesting the bronze technology was exotic. Introduction of Buddhism in China in the Han period might be associated with the spread of the bronze technology, since high-tin bronze wares were often used as Buddhist objects in China. Successive developments of binary high-tin bronze vessels in China remain uncertain, since few chemical analyses of the vessels were carried out. For example, a bronze vessel from Rentaishan Tomb 1 in Nanjing in the Eastern Jin period is apparently parallel to *sahari* vessels from a morphological viewpoint, but no chemical analysis have been conducted (橋詰 1999). It seems also that some bronze vessels from the tomb of Feng Sufu (early 5th century AD) in the Northern Yan period include binary high-tin bronze wares (Han 2009).

Diffusion of binary high-tin bronze wares from China into the Korean Peninsula also remains uncertain, since few chemical analyses of bronze bowls before the fifth century AD were conducted. Since the Unified Silla Kingdom period, however, Type A1 binary high-tin bronze vessels have been identified through the Goryeo and Joseon periods in Korea. Some of the vessels contain c. 22% Sn, which is relevant to hot forging. In addition, *sahari* vessels possibly from Silla in the collection of the Shosoin suggest both techniques of casting had forging were performed in Korea.

The earliest bronze bowls in Japan appeared in the Late Kofun period (6th to 7th century AD). However, provenances of the bowls and later collections in the Shosoin and the Horyuji temple have not yet been confirmed. Studies of *sahari* vessels in the collection of the Shosoin suggest that the collection contains both of Silla and local bronze vessels. Analyses of lead isotope ratios of the samples also support the result (馬淵 1994). Unfortunately, morphological analyses have not allowed us to distinguish Korean and Japanese bronze vessels. So far, lead-free binary high-tin bronze vessels have not confirmed in the Kofun period. Hot forging and thermal treatment techniques remain unclear, since no metallographic examinations of the samples have been conducted. From morphological viewpoints, hot forged samples have not been confirmed, but there are cast samples, including water bottles, bowls with stand, and lids with *hoju* (sacred jewel) shaped knob. The objects often contain lead, suggesting no forged samples are included. For this reason, bronze bowls from the Kofun period would consist of cast samples in principal. Morphologically, only bronze spoons were fabricated through forging in the *sahari* collections of the Shosoin and the Horyuji temple of the Nara period. Those examples may indicate that casting was the major fabrication technique of binary high-tin bronze wares in Japan, and that forging technique was not introduced into Japan. Further chemical analyses of samples are required in order to answer the questions. It is, however, significant that a series of lead-free bronze wares with c. 22% Sn content, which is a typical proportion of hot forged binary high-tin bronze wares, discovered in Japan. Nevertheless, those bronze wares were fabricated through casting, suggesting the exotic tradition of binary high-tin bronze wares was partly introduced into Japanese bronze technology.

Diffusion of the binary high-tin bronze technology from India into Southeast Asia also remains uncertain, since binary high-tin bronze vessels in Southeast Asia might be imported from India. For example, bronze vessels from Ban don Taphet include bowls with projected base that resemble to Indian bronze vessels. However, there are many tin mines in Southeast Asia, suggesting binary high-tin bronze wares were locally produced since the fourth century BC.

Lastly, this paper briefly summarizes percussion instruments (e.g. *dora*) associated with binary high-tin bronze wares. Binary high-tin bronze cymbals have been produced in modern India, but the origins of the instrument remain unclear. Concerning bronze vessels, India and Southeast Asia have close connection as has seen at Ban don Taphet, but information for cymbals in the two areas is insufficient to indicate there relationship. Because so-called *dora*s flourished in Southeast Asia, the instruments might have developed indigenously. Modern Southeast Asian *dora*s often consist of Type A1 Binary high-tin bronze wares with c. 22% Sn (Goodway et al. 1987). Binary high-tin bronze percussion instruments in China have been attested since the Northern Song period, based on chemical analysis. In the Korean Peninsula, no *dora*s were confirmed in the Unified Silla Kingdom period. Dates of *dora*s in the collection of the Shosoin and Horyuji temple are later than the Nara period, suggesting binary high-tin bronze vessels and percussion instruments were introduced into Japan in deferent periods. In Japan, *dobatsu*s or cymbals used as a Buddhist object, *dora*s with flat drumhead and *dora*s with a protuberance on the center used as an instrument of the Japanese tea ceremony might come through different routes from the origins. For example, it is assumed that *dora*s with a protuberance on the center came from Southeast Asia to East Asia, and that *dobatsu*s and *dora*s with flat drumhead spread through the same route as Buddhist objects. In order to confirm the assumptions, further investigations are required.

***Acknowledgements***

I am very grateful to many researchers that provided invaluable comments and suggestions for the manuscript, especially A. Konasugawa, H. Kuma, H. Mifune, D. Mochida, K. Nagae, T. Niwa, H. Sawada, A. Uesugi, and T. Uno.

**The manufacture process and heat treatment of high-tin bronze in modern India and South Korea: a report on the temperature controlled in hot working and heat treatment**

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***1. Introduction***

Bronze is an alloy of copper (Cu) and tin (Sn). By adding tin a melting point of copper as a mother metal (Cu) decrease and at the same time its physical property is improved. A history of bronze alloy goes back to the age before the Christ and it has been used since the ancient times. When more than 10% Sn is included it becomes hard to be cold-worked and is generally called high-tin bronze. Bronze including about 16-25% Sn is fragile at room temperature but becomes hard and tough by specific heat treatment, such as solution heat treatment and quenching. Bronze including more than 25% tin is difficult to carry out quenching and is so fragile that its usage is limited to some sort of objects such as mirrors. Even if quenching is successful its brittleness does not improve very well because $\alpha$ phase disappears in its metal structure. This paper focuses on high-tin bronze including 16-25% tin (hereafter "heat-treatable high-tin bronze" in this paper), of which is metal structure and physical property changed drastically through heat treatment. The heat-treatable high-tin bronze is very difficult to process by cold-working. So it is processed to the shape of bowls or gongs by the method so-called hot-workings at certain temperature.

The following techniques are required for the manufacturing of high-tin bronze products. Firstly, in order to fix the ratio of each metal in alloy, the ingot of copper and tin must be weighed precisely. To make vessels a regular shape their size must be measured as they are worked. Furthermore, heat-treatable high-tin bronze requires for forging and quenching after the solution heat treatment which is carried out at appropriate temperature during certain length of time. This requires for technique to precisely control the temperature and time. That is to say, in order to make excellent bronze products, the keys are the technologies to measure the length, weight, time and temperature. It might seem to be easy to measure the length and weigh and not so difficult to measure time. However, it is not easy to measure the temperature precisely. Moreover, in order to measure high temperature such as 600-800 ℃ , the advanced technology such as a sensor technology is needed. To hand over the know-how of heat processing technology from some craftsmen to its successors, it is important to teach appropriate temperature of both hot-working and quenching. However, it was probably impossible in ancient time to write an instruction manual, which, for example, mentions that "heat a bowl to 520℃ or higher…". It is likely that ancient craftsmen judged the temperature for heat treatment and hardening by looking at the colors of heated copper and did not really know its precise temperature to be taught to their apprentices. Even in the modern times, where sensor technology has been developed and various methods to measure temperature are available, the temperature has not been measured with these instruments at traditional workshops of high-tin bronze tools. On the other hand, as traditional technology has recently been declining, collecting the data about the temperature employed for hot-working and quenching and handing them down to next generations is really important. However, no references are currently available for the scientific data concerning the temperature for hot-working and quenching in the production of heat-treatable high-tin bronze.

We have started the survey of Korean bronze wares in South Korea in 2007, aiming to investigate ancient manufacturing technology of high-tin bronze wares in detail by comparing the microstructures of the modern and ancient high-tin bronze wares. It is very important that a working process, temperature for heat treatment, and metal structure of bronze ware are made clear. Temperature at casting and heat treatment as well as processing technology were investigated at six workshops in Bonghwa and Gimcheon in February 2008, and in Gimcheon, Geochang and Boseong in August 2008. Also, workshops in south India were surveyed in February and September 2009. By using a thermocouple the temperature can be measured most accurately. However, when the manufacturing work is suspended by our survey or its efficiency decreases by our interruption, it is doubtful that whether the temperature is appropriately being measured or not. Thus, we decided to employ an infrared thermometer which allows us to measure the temperature without contacting the objects. This paper mainly reports hot forging and solution heat treatment for quenching. The temperature distribution and the range of temperature of the products during hot-working, and the solution treatment temperature for quenching are discussed.

## *2. Heat-treatable high-tin bronze*

### 2.1. Temperature and phase transition of heat-treatable high-tin bronze

Fig. 1 shows Cu-Sn binary alloy phase diagram[1]. It demonstrates composed phases when bronze alloy with a certain composition is heated at a certain temperature for a certain time until it becomes equilibrium. When Sn is added to Cu, Cu is replaced by Sn. A Cu atoms form a crystal of a face centered cubic (FCC) structure. FCC structure has many slip systems and shows high malleability due to its highly symmetric structure. Even if Cu is replaced by Sn, FCC structure is kept to a certain amount. It is called α solid solution. Sn can be soluble to α solid solution up to 16% in maximum, and it keeps the state by rapid cooling even at normal temperature. It is called super saturated solid solution. It naturally has high malleability because FCC structure remains. However, when heat-treatable high-tin bronze is molten and cooled, an extremely fragile intermetallic compound phase called δ phase appears besides α phase. Delta(δ) phase has complex structure and is fragile like glass. When being shaped into objects, this fragile phase causes a breakage of a whole object. Therefore, removal of δ phase is important for high-tin bronze working and for durability of its products. For heat-treatable high-tin bronze, δ phases disappear and a part of them turns to γ phase by heating at more than 520 ℃, as shown in Fig, 1. Furthermore, γ phase turns to β phase by heating at more than 586 ℃. Beta( β ) phase is body centered cubic (BCC) and super saturated solid solution, which has high malleability. Gamma(γ) phase is an intermetallic compound based on BCC. It is softer and more plastic than δ phase, although less suitable to work than α phase[2].

By the way, most of the heat-treatable high-tin bronze products, such as Korean bronze wares and bowls and gongs in India, include 22% of Sn in their composition (hereafter Cu-22Sn). To examine the transformation temperature of Cu-22Sn alloy, as shown in Fig. 1, a thermal analyzing test (DSC) was carried out. Fig. 2 shows the results, in which endothermic peaks A to D were observed. A (524℃) is an endothermic peak of the transformation from δ phase to γ phase. B (580℃) indicates the transformation from γ phase to β phase. And C (802℃) indicates that a part of solid phases has transformed to liquid phases. The ratio of the liquid phase at this moment is calculated to 70% by the lever low which is referred to in the diagram of Fig. 1. The amount of liquid phases increases as the temperature raises, and it is completely turns to liquid phases at D (875 ℃). All the transformation points in Fig. 1 were verified by the thermal analyzing test. It is said from the results of Izod impact strength test[2] that the most suitable temperature for hot working is approximately 530-650℃. The results of thermal analysis also suggest that it needs to be worked at the temperature between 524℃ and 800℃. Further, in order to strengthen toughness of high-tin bronze products at normal temperature, quenching is necessary in order to remove δ phase. It is thus heated to 586-800℃ and then rapidly cooled. We investigated the temperature conditions in hot working and solution heat treatment for quenching at workshops of high-tin bronze wares at various workshops in India and South Korea.

### 2.2. The history of the treatment of high-tin bronze and its general metal structure

Microstructure of bronze alloy varies depending on its composition or methods of working. That is to say, the analysis of its metal structure can tell us its manufacturing process and whether it was heat treated or not. Prefatory Photos 33-36 show the metal structure of Cu-22Sn alloy manufactured in APPUNI’s workshop in Palakkad, Kerala, India. Photo 33 shows the microstructure of a cast example. Alpha phase dendrites, which have grown in the process of solidification, and α + δ eutectoid are observed. By hot-forging, dendrites are divided into recrystallized structures in which isometric α phase is distributed uniformly, as shown in Photo 34. In both cases they are too brittle for cold-forging due to δ phase. Photo 35 shows a structure, which was heated, after hot-forging, at more than 586 ℃ in order to transform δ phase to β phase and then quenched into water to prevent re-precipitation of δ phase. Isometric α phase with annealing twin and β’ martensite structure are observed. Photo

36 shows a similar structure to Photo 35, but many lines looking like polishing scraches appear in α phase and β phase. These are called slip-lines and indicates cold-forging. The presence of slip-lines demonstrates that the structure of quenched metals is as malleable as normal metals.

### *3. Temperature measurement*

An Infrared thermometer (NEC San'ei TH9100MR: hereafter "thermo tracer") was employed. This is the device which converts infrared radiations emitted from a target object to electric signals and displays them as a color thermo image. Radiation of infrared rays varies depending on materials, so it is needed to select a suitable emissivity according to the objects or the condition of their surface. It is thought that the measurement is difficult especially for metallic materials because their radiations vary extremely according to the states of their surface and their temperature. In the previous reports[3], we measured the black surfaces of objects which was oxidized by repeated heat workings such as forging, using the radiation for black copper oxide, i.e. $\varepsilon$ =0.88, by referring to a table of radiations given in the operating manual of the device[4]. However, it seems to have been inaccurate for the evaluations of temperature in hot-workings and quenching, which are estimated to be about 600-700 ℃, because the value of radiations given in the table is for the case of 100℃. Therefore, we looked up the relevant literature and identified that the radiation of oxidized copper at 538℃ is $\varepsilon$ =0.77 [5]. Using this value of radiation we re-evaluated the data of the measurement of temperature, including the data previously reported. To measure temperature using a thermo tracer, one is advised to consider the noise (incident infrared rays from objects other than the target) and thus bronze products heated in a furnace are difficult to measure with this instrument. Thus, before we move to the discussion below, it is necessary to acknowledge that the data shown in Prefatory Photos 41, 55, 56 and 59 were collected under such conditions.

### *4. The results (the temperatures of hot-working and heat treatment)*

#### 4.1. India

Six workshops in Kerala were surveyed in February and September 2009. Two workshops manufacture bowls and gongs by hot-forging of heat-treatable high-tin bronze in a traditional way. The survey results of the temperature measurement during the hot-working and the heat treatment for quenching are described below.

**1) E.T. APPUNI (KALADIPARAMBIL CHERUKUDANGADU PALAKKAD DIST. KERALA, INDIA)**

Bowls, spoons, disc gongs, and cymbals are manufactured in E.T. APPUNI's workshop. Temperature of hot-workings was measured here during the manufacture of bowls by the workshop owner and his three relatives. Firstly, molten Cu-22Sn is poured into a hollow in sand mold to make a disc, a blank which is forged to a bowl (Prefatory Photo 3). We tried to measure the temperature while it is being poured but it was difficult to measure it precisely because the surface of the molten bronze is immediately covered with an oxide layer. Although the radiation of molten Cu is $\varepsilon$ =0.13-0.16, we used the radiation of an oxidized layer, $\varepsilon$ =0.77, because the raw surface of Cu was hardly exposed. The temperature was approximately 1170 ℃. Although its accuracy is still in question, the data of molten metal is given here just for reference. Cast discs are forged in order to form gongs, cymbals or bowls. At first, a gong was formed. Temperature was measured fifteen times during its process. The highest temperature was 764 ℃ and the lowest 600 ℃ with the average of 685℃. The edge of the disc gong was fractured. In the afternoon, cymbals were manufactured and eleven data was obtained. The temperature of hot-working of the cymbals were 753 ℃ in maximum, 575℃ in minimum and 687℃ on average. This process was carried out at relatively high temperature and, as in the case of the gong, a fracture occurred while forming a central dent.

The next day, bowls were produced. Bowls were formed by forging a pile of a few plates. As its process progresses, more plates were added to one pile. Prefatory Photo 37 is a thermo image of a pile of six plates being forged and Prefatory Photo 38 is its visible image. These images were taken at the beginning of forging process which started when APPUNI judged that the bowls placed on a furnace had been heated to relevant temperature. The temperature on average was 740℃. Prefatory Photo 39 of a thermo image was taken while the forging was suspended once, immediately before it was reheated. As seen in a visible image of Prefatory Photo 40, it was suspended when reddish color still remained. The temperatures on average was 630℃ at this moment. In total, forty data was obtained during the process of bowl manufacture, and they were 780℃ in maximum, 556℃ in minimum and 680℃ on average. A part of Cu-22Sn alloy transforms to liquid phase at 800℃. So these temperatures can be considered to be very high. The average temperature in hot forging of bowls was almost the same as or only slightly lower than that for gongs and cymbals, for which fracture occurred. Nevertheless, bowls were not fractured.

Bowls shaped by hot forging are easy to break because their metal structure contains an extremely fragile intermetallic compound, $\delta$ phase. To exclude $\delta$ phase and to strengthen them, quenching was carried out. Prefatory Photo 41 is a thermo image during heating for quenching. The temperature of the bowl was 730℃ on average. This temperature is within the range that $\delta$ phase completely transforms to $\beta$ phase. However, the actual temperature might be slightly lower because it might have received the signals, as a noise, from the furnace on which the bowls being measured were placed. Even so, the heating temperature required for hardening is more than 586 ℃ and the hardening must have been carried out without any problems because the margin of error in this measurement would not be so large.

**2) K.R. SUKU (ALA FORGE: KOPARAMPATHU KADAVALOOR TRISSUR DIST. KERALA, INDIA)**

SUKU's workshop (ALA FORGE) mainly manufactures gongs and cymbals. He is a distant relative of APPUNI. Four brothers including him were working here together.

Firstly, a disc was cast as in the case of APPUNI's workshop. Then it was shaped by hot forging. The temperatures during hot-working to form a gong were measured and the results are as follows. Prefatory Photo 43 is a thermo image of a disc at the beginning of forging (and Prefatory Photo 44 is its visible image). The temperature of the disc was 632℃ on average. Prefatory Photo 45, a thermo image, was taken when forging was suspended once, immediately before it was re-heated. The temperature was 546 ℃ on average. Reddish color of the disc had already disappeared at this moment, as seen in the visible image (Prefatory Photo 46). Measurement was taken fifteen times during hot-working of a gong at this workshop. The results were 725℃ in maximum, 546℃ in minimum and 646℃ on average. It shows that the gong was formed within a considerably lower range of temperature when compared with APPUNI's workshop. It is known that the most suitable temperature for hot working of Cu-22Sn alloy is 530-650℃. Although the results show the temperature slightly higher than it, no fracture was observed in the manufacture of the gong.

The gong is also quenched to improve its brittleness at normal room temperature. Prefatory Photo 47 is a thermo image of the gong immediately before quenching. With our thermo tracer there is a little time lag in recording a thermo image and a visible image (a visible image is recorded later). Prefatory Photo 48 is a visible image saved at the same moment as Prefatory Photo 47. However, the thermo image of 47 was recoded while the gong is being carried from a furnace to a water tank while 48 was recorded when the gong was just quenched in water. That is to say, the data in 47 demonstrates the temperature just before dipping the gong into water. At this moment, the temperature of the gong was 725 ℃ on average, which was almost equal to the case at APPUNI's workshop.

**4.2. South Korea**

In South Korea, the manufacture of high-tin bronze tools made of Cu-22Sn, called Korean bronze ware, “Yugi”, is still in action today. In total, six workshops of yugi were surveyed in February and August 2008. This chapter discusses the results of the survey which investigated the temperature of heat treatment for quenching at two workshops for cast yugi in Bonghwa, the temperatures for hot-working and quenching of forged yugi in Gimcheon, the temperature for hot press working in modern yugi factory in Geochang, and the temperature for hot-working of Ban-Bangjja yugi by Gung Gurum technique.

**1) Go Tae Ju (Bonghwa)**

The origin of yugi in Bonghwa can be traced back to 500 years ago[6]. Go Tae Ju's workshop have manufactured yugi for 100 years, and now produces bowls, chopsticks, spoons, kettles, incense burners and other various products by casting. The temperature of molten metal in a casting process was about 1160 ℃. Because cast products composed of $\alpha$ phase and $\alpha+\delta$ eutectoid are hard and brittle, heat treatment for quenching is performed. The heating temperature for quenching was about 670 ℃. The temperature of the products was easily observed because it was dim in the workshop. The temperature of heat treatment carried out at this workshop might be lower than that for the manufacture of bowls in India. From a viewpoint of the transformation of metal structure, $\delta$ phase disappears without any problems in either case.

**2) Kim Sun Ick (Bonghwa)**

Kim Sun Ick's workshop was founded 200 years ago. Bowls, chopsticks, spoons and other various products are manufactured here, as well as Go Tae Ju's workshop. The heating temperature for quenching was 645℃.

**3) Kim Il Oung (Gimcheon)**

Kim In Oung in Gimcheon has been designated to the intangible cultural property in Gyeongsang-buk-do No. 9. His workshop manufactures Bangjja yugi and cast yugi. Bangjja yugi are relatively large products, such as gongs, made by hot-forging. The survey results represented below are the temperatures of hot-forging and quenching in a traditional manufacture process of Bangjja yugi and the temperatures in a hot-forming process of bowls by a modern method such as spinning.

Firstly, Prefatory Photo 49 is a thermo image of the edge of a gong being forged through a Bangjja process. Not a whole gong was heated but the parts to be formed were only heated. This is because the gong is very large. Therefore, the temperature of the part being worked was 690℃ on average while the edge on the other side was about 420℃. Then, the inside of the gong was forged by two persons. Prefatory Photo 51 is a thermo image at this moment. Although a little difference was present in its temperature it was almost even and the average was 660 ℃. Temperatures were measured twelve times during hot-workings of the gong. The results were 713℃ in maximum, 566℃ in minimum and 657℃ on average. This demonstrates that the work continued even at considerably low temperature, when considering that Cu-22Sn alloy suddenly becomes fragile at less than 550℃. The working room where the gongs are formed has no window and thus quite dim. Even slightly reddish color of the gong can easily be distinguished there, so it seems likely that the hot-working can be continued right until the temperature of the gong decreases to the risky point where fracture could occur. After being shaped, the gong is heat-treated for quenching. The hardening temperature was 736 ℃. Prefatory Photo 53 is a thermo image of the gong immediately before quenching, and Prefatory Photo 54 is a visible image immediately after quenching. While the forging temperature was low, the heating temperature for quenching was relatively high. It is almost equal to those at two workshops in India and is higher than two workshops in Bonghwa. Probably, such a large gong has to be heated at high enough temperature in order to heat its whole part uniformly.

Kim Il Oung's workshop also manufactures bowls formed by a spinning machine. Spinning is normally applied to soft metals in a cold state. For high-tin bronze it must be carried out in a hot state in order to prevent its fracture and thus it was heated with a burner during a hot-spinning process. Although a normal sensor cannot detect the temperature of a plate spinning so fast, it is easy to measure it using a thermo tracer. Prefatory Photo 55 is a thermo image at the beginning of spin-shaping and Prefatory Photo 57 was taken at further developed stage of spin-shaping. During the spinning, temperatures were measured forty-one times. The results were 730℃ in maximum, 589℃ in minimum and 647 ℃ on average. After spin-shaped, several bowls were together put into a furnace. And after heating, they were quenched into water one by one. Prefatory Photo 59 is a thermo image of the furnace at this moment. For this image the radiation of a red brick $\varepsilon$ =0.93) was used instead of that of copper bowls. However, because this radiation ( $\varepsilon$ =0.93) is to be used at normal temperature while the data taken here is 740℃, this value should be reconsidered with a more appropriate radiation in further study. This image demonstrates that temperatures of these bowls vary depending on their positions in the furnace. The difference between the highest and lowest was about 100℃. The workers changed the positions of these bowls as they inspect the inside of the furnace and quenched them one by one in a large vessel filled with water from the bowl which was heated to the relevant temperature.

**4) Lee Sun Sul (Geochang)**

This is a mass production factory using a press machine. A cast plate was spread with a roller and press-punched. Then it was formed into a bowl shape by spinning or by other methods. These processes were carried out in a hot state. Finally, the bowl was heated in a furnace, and its rim was narrowed by a press machine. Prefatory Photo 61 is a thermo image when the rim was being narrowed using a press machine. In this process, temperature was measured ten times and the results were 672℃ in maximum, 626℃ in minimum and 653℃ on average. A press-worked bowl was directly and immediately quenched in water. Therefore, the temperature of quenching is estimated at about 650℃ or slightly less.

**5) Han Sang Chun(Boseong)**

Korean bronze ware can be separated to cast yugi and forged yugi, the latter can be divided into so-called Bangjja and Ban-Bangjja. Bangjja yugi is made by the method in which a plate cast in a hollow is hammered to shape. On the other hand, Ban-Bangjja is made by the method in which a plate cast in a sand mold is forged to shape and this method includes a unique process, so-called Gung Gurum technique, to narrow the rim [3]. Han Sang chun is a successor of Ban-Bangjja yugi production.

Fig. 3 shows changes in form through the production of Ban-Bangjja yugi. P1 is a cast plate from which the production starts. This form changed to P2, P3 and P4 as it is hammered on a mortar with a hollow depression. A photo of its section demonstrates that the thickness of the plate became thinner and thinner. By narrowing the rim by Gung Gurum technique and then quenching, P4 changed to P5. The metal structure in Fig. 4 shows that P1 was composed of a dendritic $\alpha$ phase and $\alpha+\delta$ eutectoid phase. In the metal structure shown in P2, which is after forging P1, the $\alpha$ phase has turned isometric and forming of annealing twin was observed. P5 is a sample after quenching. The metal structure was composed of $\alpha$ phase and $\beta'$ martensite phase, while $\delta$ phase disappeared. More detailed metal structures of P1 and P5 are explained as follows. Fig. 5 is X-ray images of them. Top left is the distribution of Cu, top right is the distribution of Sn, and CP (bottom left) is an composite image. The X-ray images of P1 demonstrate that Cu and Sn are sparsely present since $\alpha$ phase and $\delta$ phase are minutely mixed in eutectoid structure. Nevertheless, microsegregation in the $\alpha$ phase was not observed. In the structure image (CP) of P5, $\alpha$ phase and $\beta'$ martensite with many small lines were seen. The distribution of elements in a martensite part is homogenous due to a solution treatment before quenching.

The temperatures in hot-working by Gung Gurum technique were surveyed. Prefatory Photo 63 is a thermo image in a process of Gung Gurum technique. The temperatures were measured in the same way every 0.5 seconds from the beginning of the work, and the results were plotted in Fig. 6. This work was carried out within 16 seconds while the temperature of the vessel was between 700 ℃ and 580 ℃ . Although quenching was also carried out afterward, the data was not able to be obtained because the timing of data recoding did not much the timing of a quenching process.

### *5. Summary*

In India and South Korea, the temperatures of heat-treatable high-tin bronze were measured during hot-working and quenching processes. In this research the scientific data were accumulated for the forging technologies which have been obtained by craftsmen through their intuitions and long experiences and have been succeeded from one generation to another. Table 1 summarizes its results.

In India, the temperatures were relatively high in both forging processes and heat treatment for quenching because they worked in semi-outdoor workshops during bright daytime. Possibly because of this, fractures occasionally occurred at a workshop which does not operate regularly. For Korean bronze ware, both the central and local governments provide a support, for example the designation of intangible cultural properties, in order to promote the successors of traditional technology. The workshop is deliberately made dim in order to judge the temperature of products more precisely by their color and the work was performed near the temperature most suitable for Cu-22Sn alloy.

In further studies, we would like to continue surveying the temperatures used during hot-working and heat treatment of high-tin bronze tools in other regions of Asia and, based on it, to investigate details of ancient high-tin bronze technologies in various regions.

### *Acknowledgments*

I would like to express my gratitude to those who were working at the surveyed workshops of high-tin bronze tools in India and South Korea and also to the following persons for their supports and advices.

Eun-Seok Lee, Sang-Yong Lee, Kwon Ju Han, Srinivasa Ranganathan, R.M. Pillai, Sharada Srinivasan, Vimal Kumar. V.A., Haruhisa Mifune, Yasuji Shimizu, Shin'ya Shoda, Yosuke Muramatsu

The part of the research in this paper is supported by Grants-in-Aid for Scientific Research (Nos. 21300328 and 19300299).

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## Developments of High-tin bronze in the Pre-Qin Period in China

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### *1. Introduction*

In the study on Chinese bronze production, the composition of bronze and casting technology have been intensively studied. Su argued that casting and alloying are two key-processes in the bronze production and the former is the process to shape the artifact while the latter is the process to mix raw materials and related to the function of the artifact (Su et al. 1995: p. 185). In fact, the composition of bronze reflects the raw materials and is deeply related to the function of the bronze artifact. In China, fragments of bronze artifacts are frequently analyzed, which promotes arguments on the composition of bronze.

This paper will discuss high-tin bronze. As for high-tin bronze, various studies have been undertaken in particular by natural scientists. For example, Li Minsheng pointed that lead tin bronze and lead bronze increased in number during the Shang Period. He also suggested that during the Yinxu Period elite tombs such as the tomb of Fu Hao predominantly yield tin bronze artifacts while normal tombs mostly yield lead artifacts and lead-bronze artifacts. According to him, tin-bronze and lead-bronze were differently used between different social classes (Li 1984). Su Rong-yu also pointed the shift from low-tin bronze to high-tin bronze through periods. According to him, during the Yinxu Period, high-tin bronze consisting of copper and tin or consisting of copper, tin and lead became predominant among metal alloys. After the Western Zhou Period, the ternary alloy of copper, tin and lead became predominant (Su et al. 1995). Hua Jueming divided developments of bronze vessels into three phases. In the first phase (until the Erlitou Period), pure copper and bronze containing small amount of lead and tin were used for production of bronze vessels. In the second phase (until the Erligang Period), low-tin bronze and lead bronze were used. In the third phase (after the Yinxu Period), high-tin bronze was predominantly used for the production of bronze vessels (Hua 1999).

As just mentioned, the outline of developments of high-tin bronze in China has been already clarified to some degree by the previous studies. However, amounts of high-tin bronze artifacts were analyzed after these studies. Moreover, it is also necessary to study regional differences in developments of high-tin bronze, which has not been studied yet. This paper will deal with Pre-Qin bronze artifacts and collect results of composition analyses on excavated bronze artifacts. The aim of this paper is to reexamine developments of high-tin bronze. It is generally agreed that the percentage of tin in bronze is deeply related to heat treatment techniques (Katori 1985: p. 87; Nishimura 2000; Nagae 2008)[1]. Therefore developments of heat treatment techniques will also be reviewed here as far as the author understands by reference to the reports of the analyses[2].

In the previous studies, the high-tin bronze was defined as the bronze containing more than 10% tin (Su et al 1995; Nagae 2008). Su pointed that the percentage of lead is also an important factor and divided bronze artifacts into several types (Figure 1, Su et al. 1995). According to him, high-tin bronze can be divided into three types as below.

II H: High-tin bronze containing less than 2% lead. This can be called the “binary alloy of copper and tin”.

IV S: High-tin bronze containing 2% to 10% lead. This bronze can be called “high-tin lead bronze”

IV B: High tin bronze containing more than 10% lead. This bronze can be called “high-tin high-lead bronze”.

This paper adopts his division but also focuses on the percentage of tin in bronze artifacts. The accuracy of the original data of the composition analyses were not checked by the author. This paper intends to reveal general outline of historical developments of high-tin bronze.

### *2. From the Neolithic to the Erlitou Period*

Bronze artifacts from the Neolithic to the Erlitou Period are regarded as the earliest bronze artifacts in China. So far over 500 bronze artifacts dated to these periods were discovered (Bai 2002). Several composition analyses have been done on Neolithic Bronze artifacts. For example, a Majiayao bronze sword excavated from the site of Linjia, Dongxiang in the Gansu province contains 6 to 10% tin (Sun et al. 1997). Other Neolithic tin bronze artifacts were also discovered in particular in Northwestern China. However, no high-tin bronze artifacts containing more than 10% tin were excavated from any Neolithic sites. Han Rubin suggests that in the Neolithic Period raw materials for tin-bronze were probably obtained from paragenetic deposits of copper and tin (Beijing Gangtiexueyuan Yejinshizu 1981).

In the Erlitou Period, high-tin bronze artifacts first appeared in China. For example, several high-tin bronze artifacts including a ring headed sword (Phase3, 15.4% tin, II H), *He* (wine vessel) (Phase4, 13.9% tin, IV B), fish hook (Phase4, 23.09% tin, IV B), arrowhead (Phase4, 10.41% tin, IV S), chisel (Phase4, 14.15%, IVB), and bar (Unknown phase, 17.04% tin, II H) were excavated from the site of Erlitou, Yanshi in the Henan province in the middle Huang *He* region (Li 1984; Qu et al. 1999; Hayakawa et al 1999). An awl excavated from the site of Yinjiachen, Sishui in the Shandong province in the lower Huang *He* region is also made of high-tin bronze and contains 15.12% tin (IV S) (Beijing Kejidaxue Yejinshi Yanjiushi 1990). The site of Zhukaigou in inner Mongolia yielded bronze artifacts, which can be dated to the lower Xiajiadian Period to Shang Period. The lower Xiajiandian bronze artifacts contain several high-tin bronze artifacts such as a needle (10.6% tin, IV S) and two earrings (12.5% tin, IV S and 17% tin, II H). In addition, some of the artifacts were probably treated by annealing and cold-work (Li et al. 2003)[3]. According to Sun Shuyun, 3 tin bronze artifacts, which were excavated from the Siba site of Ganguya, Jiuquan in the Gansu province contain over 10% tin (Sun et al. 1997). It is also reported that a lower Xiajiadian earring excavated from the site of of Xiaoguanzhuang, Tangshan in the Hebei province contains over 10% tin (Beijing Gangtiexueyuan Yejinshizu 1981). It is also worth noting that a lead bronze sword containing 32% lead, which was excavated from the site of Yinjiacheng, Sishui in the Shandong province, were probably processed by hot-forging. A Qijia copper awl was also said to be processed by hot-forging (Beijing Kejidaxue Yejinshi Yanjiushi 1990).

### 3. Shang Period

As for the Erligang Period, bronze artifacts were analyzed throughout China. Bronze artifacts excavated from a pit discovered in Nanshunchengjie, Zhengzhou Shangcheng include high-tin bronze vessels such as *Gui* (cup) (13% tin, IV S) and *Fangding* (sacrificial vessel) (17.8% tin, IV B) (Sun 1999). Other high-tin bronze artifacts such as *Ding* (sacrificial vessel) (13.4% tin, II H), *Pan* (dish) (10.9% tin, II H) and *Jia* (cauldron) (10.7% tin, IV S) were excavated in Zhengzhou (Henansheng Wenwuyanjiusuo et al. 1983, He 1997). According to Tian Changhu, a bronze *Jia* (cauldron) excavated from Changzhi in the Shanxi province were probably processed by annealing (Tian 1985). A *Jue* (cup) (14.995% tin, IV S), *Ding* (sacrificial vessel) (11.542% tin, IV B), *Jia* (cauldron) (15.576%, IVS ) excavated from Yuanqu Shangcheng in the *Shanxi* province were also high-tin bronze (Yao 1996). In the Chang Jiang region, bronze vessels excavated from the site of Panlongcheng, Huangpo in the Hubei province were intensively analyzed by Hao Xin. Most of the vessels were high-tin bronze (IV B) and contain more lead than bronze artifacts discovered in Zhengzhou (Figures 2 and 3) (Hao et al. 2001). However, He Tangkun also analyzed other bronze artifacts excavated from Panlongcheng and suggests that the artifacts contain less lead and tin than those analyzed by Hao (He 2001). Hao Xin also pointed that some of the bronze were processed by hot-forging after casting (Hao et al. 2001). As for the northern region, the site of Zhukaigou in inner Mongolia yielded a total of 12 high-tin bronze including a shaved knife (35.9% tin, II H) , three vessels (IV B), six weapons/tools (IV S: 5 pieces, II H: 1 piece), a fragment of circle stand (II H) and earring (II H) (Li and Han 2000). The site of Zhangying, Changping in Beijing also yielded two high-tin bronze including an arrowhead (17% tin, II H) and sword (26% tin, II H) (Cui et al. 2007).

In the Yinxu Period, high-tin bronze artifacts became more predominant (Su et al. 1995; Hua 1999). Some scholars suggest that the use of high-tin bronze artifacts clearly reflect the social hierarchy (Li 1984). In fact, the tomb of Fu Hao, who was probably a queen, yielded amounts of high-tin bronze artifacts. 112 artifacts excavated from her tomb were analyzed. Of 112, 110 artifacts were high-tin bronze artifacts. In addition, the samples did not contain any high-tin high-lead bronze (IV B) containing more than 10% lead (Figure 4) (Zhongguo Shehuikexueyuan Kaoguyanjiusuo Shiyanshi 1982; Zhengzhougongxueyuan et al. 1982). Excavations in the west area of Xiaotun in Yinxu revealed that in the early period most bronze vessels were made of high-tin bronze while weapons were mostly made of lead bronze. It is also clarified that in the late period lead was used for production of bronze vessels and tin was used for production of weapons (Figure 5) (Li et al. 1984). Zhao Chunyan recently analyzed approximately 200 bronze artifacts excavated from the site of Yinxu. According to her, the use of tin for production of bronze vessels gradually decreased. In contrast, tin was replaced by lead for production of bronze weapons by Phase3 although the use of lead for production of weapons decreased again in Phase4 (Zhao 2004)[4]. As for heat-treatments, Junko Uchida studied Yinxu bronze artifacts stored at Zhongyangyanjiuyuan Lishiyuyanyanjiusuo and revealed that a dagger-axe show homogenous micro structure. She suggests that the structure is probably caused by tempering [5](Uchida et al. 2009).

Bronze artifacts excavated from the tomb of Jingjie, Lingshi in the Shanxi province contain more copper than those excavated from the site of Yinxu and the percentage of copper is usually over 90%. The tomb yields only one high-tin bronze artifact, *Zun* (sacrificial vessel), which contains 13.2% tin (IV S). According to Chen, this vessel does not show any traces left by heat treatments but other artifacts were heat-treated. In addition, some of the artifacts show clear segregation by casting (Chen et al. 2006). Two high-tin bronze *Bu* (small jars) (18.7% tin, IV S and 15.85% tin, IV S) were excavated from the site of Nianzipo, Changwu in the Shaanxi province (Mei et al. 2007).

In the Chang Jiang region, 20 bronze artifacts excavated from the tomb of Dayangzhou, Xingan in the Jianxi province, were analyzed. Of 20 samples, 10 were made of high-tin bronze, which contain five vessels (18.44% tin at maximum, IV S: 4 pieces, II H: 1 piece), and five weapons/tools (34.03% tin at maximum, IV S: 2 pieces, II H: 3 pieces) (Fan et al. 1997). Su Rong-yu identified the single $\delta$ phase in the micro structure of trim knife and engrave knife and suggested that these bronze artifacts were processed by quenching (Fig. 6) (Su et al. 1997)[6]. 13 bronze artifacts excavated from the site of Sanxingdui, Guanghan in the Sichuan province were analyzed. Of 13, 7 were made of high-tin bronze. They include 5 vessels (18.6% tin at maximum, IV B: 2 pieces, IV S: 2 pieces and II H: One piece), a dagger-axe (12.3% tin, IIH) and a plate (10.2% tin, IV S) (Jin et al. 1999).

### *4. Zhou Period (Western Zhou, Spring and Autumn, Warring State Periods)*

#### (1) Huabei Region

162 bronze artifacts excavated from the cemetery of Yu clan (Zhifangtou, Zhuyuangou and Rujiazhuang), Baoji in the Shaanxi province were analyzed. Of 162, 82 are high-tin bronze artifacts (22% tin at maximum, II H: 21 pieces, IV S: 34 pieces, IV B: 27 pieces). They are mostly made of ternary alloy of copper, tin and lead. The single $\alpha$ phase identified in the microstructure of a head mask for horse (9.97% tin, excavated from No. 7 tomb of Zhuyuangou) and *He* vessel having bird shaped handle (The composition is not reported. It is excavated from No.2 tomb of Rujiazhuang) suggests that these artifacts were processed by annealing. No. 9 tomb of Zhuyuangou, which is dated to the middle Western Zhou Period, yielded tin *Ding* (sacrificial vessel) (90.69% tin) and tin *Fu* (dish) (87.13% tin). No.2 tomb of Rujiazhunag also yielded tin fish shaped plate (98.95% tin) (Su et al. 1988, Su et al. 1995)[7]. It is also worth noting that the cemeteries discovered in the villages of Qucun and Tianma in the Shanxi province, which are dated to Western Zhou Period to the Early Spring and Autumn Period, yielded amounts of tin artifacts (Beijingdaxue Kaoguxuexi Shangzhouzu et al. 2000). Han Rubin analyzed a bronze dagger-axe excavated from No. 152 tomb of Zhangjiapo, which is dated to the middle Western Zhou Period and concluded that the composition of the cutting part of the dagger axe contain 22.5 % tin and the dagger axe was processed by annealing and cold work (Han 1995). 10 Early Western Zhou bronze artifacts excavated from the cemetery of Liulihe, Beijing were analyzed. Of 10, 8 were made of high-tin bronze (15.983% tin at maximum, II H: 6 pieces, IV S: 2 pieces). The percentage of lead in these artifacts is low and less than 10%. Traces left by hammering were identified on a dagger axe (He 1988). 30 bronze artifacts excavated from the cemetery of Guo clan, Sanmenxia in the Henan Province, which is dated to the late Western Zhou Period, were analyzed. Of 30, 23 were high-tin bronze (25.2% tin at maximum , II H: 2 pieces, IV S: 12 pieces and IV B: 9 pieces) [8]. The microstructure of one *Fanghu* (jar) (14.5% tin, IV S), *Fangyan* (tall

vase) (8.2% tin), two *Ding* (sacrificial vessel) (11.4% tin, IV S and 11.2% tin, IV B), one *Gui* (dish) (12.4% tin, IV B) and one *Pan* (dish) (4.7% tin) suggest that they were heated after casting (Li et al. 1999).

33 bronze artifacts excavated from No.251 tomb in Jinshengcun, Taiyuan in the Shanxi province were analyzed. They are dated to the late Spring and Autumn Period and mostly high-tin bronze (II H: 2pieces, IV S: 23 pieces, IVB: 8 pieces). These samples were analyzed by the atomic absorption spectrometry and energy dispersive X-ray spectrometry. The former shows higher percentage of lead than the latter (Sun 1996). 30 bronze artifacts excavated from the tomb of Chengcun, Linyi in the Shanxi province were analyzed. They are dated to the middle and late Chunqui Period. The 30 samples include 19 high-tin bronze artifacts (19.95% tin at maximum, II H: 3 pieces, IV S: 2 pieces, IV B: 14 pieces) (Li 2003). 59 bronze excavated from the cemetery of Fenshuiling, Changzhi in the Shanxi province were analyzed, of which 54 were high-tin bronze (19.95% tin at maximum, II H: 7 pieces, IV S: 26 pieces, IV B: 22 pieces). The cemetery is dated to the middle Spring and Autumn Period to Warring State Period. In addition, a variety of bronze artifacts such as vessels, music instruments and weapons were probably treated with annealing (Han et al. 2010). 63 bronze artifacts excavated from a ritual pit in Xinzheng in the Henan province, which are dated to the middle and late Spring and Autumn Period, were analyzed. Of 63, 12 were made of high-tin bronze (12.7% tin at maximum, II H: 1 piece, IV S: 7 pieces, IVB: 4 pieces) (Huang et al. 2006). 18 Warring State Period bronze artifacts excavated from the cemetery of Houchuan, Shanxian in the Henan Province were analyzed, of which 4 were high-tin bronze (14.86% tin at maximum, II H: 1 piece, IV S: 2 pieces, IV B: 1 piece) (Zhongguo Shehuikexueyuan Kaoguyanjiusuo Shiyanshi 1994). 9 Late Spring and Autumn bronze artifacts excavated from the tomb of Fenghuangling, Lin-yi in the Shandong Province were analyzed. All of the samples were high-tin bronze and contain little lead (Shandonsheng Yanshitielu Wenwukaogugongzuodui 1988).

**(2) Huazhong Region**

In the lower Chang Jiang region, a number of “” Wu” type bronze artifacts, which are dated to Western Zhou and Spring and Autumn Periods, has been analyzed, which revealed that the “Wu” type bronze contain amount of tin and lead. Zeng Bin analyzed 80 samples. Of 80 samples, 63 were high-tin bronze (40.14% tin at maximum, II H: 9 pieces, IV S: 36 pieces, IV B: 18 pieces). These artifacts also contain amount of lead. His analyses showed that the percentage of lead decreased and that of tin increased through periods[9] (Zeng et al. 1990). It is reported that a middle Western Zhou sword with 23 % tin excavated from Gaochun, Jiangsu and late Spring and Autumn dagger-axe with 23% tin excavated from Dantu were processed by quenching. Annealing on weapons was also reported (Xiao et al. 2004; Jia et al. 2004). As for the Warring State Period, all of the analyzed samples, which were excavated from the tomb of Gaozhunag, Huaiyin, were made of high-tin bronze (Sun et al. 2009).

As for the middle Chang Jiang region, Spring and Autumn bronze artifacts excavated from the tombs of Xiasi, Xichuan in the Henan province and tombs of Zhaojiahu, Yichang, in the Hubei province contain 5 to 15 % lead and tin (Li et al. 1991; Sun 1992). Most of the bronze artifacts excavated from No. 1 tomb (early Warring State Period), No2. Tomb (middle Zhanguo period) in Leigudun, Suizhou in the Hubei province and the tomb of Baoshan (the late middle Warring State Period), Jingmen in the Hubei province are type IV S of high-tin bronze. They include *Gui* (cup) containing 41.2% tin. In particular, it is reported that the bronze excavated from the tomb of Baoshan were processed by hammering and annealing (Jia 1989; Huang et al. 2008; He 1991). Bronze artifacts excavated from the tombs of Zuozhong, Jingmen in the Hubei province were mostly made of high-tin bronze and occupied by IV B and IV S types. It is also reported that they were heat-treated and traces left by hot forging can be observed. They include shaved knife containing 27.47% tin (Luo et al. 2006)[10].

It is also noteworthy that No. 8 tomb of Zhaojiapang, Yichang in the Hubei province, which is dated to Spring and Autumn Period, yielded a tin *Gu* (cup) (Sun 1992) and the tomb of Geling, Xincai in the Henan province, which is dated to Warring State Period, yielded 80 tin artifacts such as combs (Henansheng Wenwukaoguyanjiusuo 2003).

**(3) The Huanan Region**

8 bronze artifacts including arrowhead, axe, dagger axe and bell, which were excavated from

the cemetery of Henglingshan, Boluo in the Guangdong province were analyzed. They are dated to the Western Zhou and Spring and Autumn Periods. Of 8 samples, 6 were made of high-tin bronze artifacts (11.4～20.3% tin, II H; 2 artifacts, IV S; 3 artifacts, IV B; 2 artifacts). It was also reported that the microstructure of suspension of the bell show the inverse segregation (Sun 2005). Warring State high-tin bronze artifacts were also discovered from archaeological sites and studies on the microstructure on the artifacts reveled that bronze were processed by annealing (axe and *Ding*) and quenching (tearing knife excavated from Luoding in the Guangdong province (19.5% tin, II H)). The cemetery of Wanjiaba, Chuxiong in the Yunnan province yielded tin ornaments (Qiu et al. 1983).

**(4) Other Regions**

7 bronze artifacts excavated from the Siwa cemetery of Xujianian, Zhuanglang in the Gansu province were also analyzed. Of 7, only one arrowhead was made of high-tin bronze (14.4% tin, IV S) (Zhao 2006). As for northeastern China, the results of analyses on 64 bronze artifacts discovered in the Liaoxi area were reported in the paper by Zhang Riqing. Although the details are not clear due to the lack of reference, he suggests that tin lead bronze including high-tin bronze were predominantly used (Zhang et al. 1982).

### *5. Conclusions*

On the basis of the above reviews, this section will discuss the developments of high-tin bronze and heat treatment techniques during the Pre-Qin Period.

It was in the middle and lower Huang *He* regions and Great Wall region that high-tin bronze artifacts, which contains more than 10 % tin, appeared for the first time in the Erlitou Period. Although the composition of these high-tin bronze artifacts varies to a degree, some of the artifacts were already heat-treated by simple techniques. In the Shang Period, the binary alloy of copper and tin (Type II H) and ternary alloy of copper, tin and lead (Type IV S and Type IV H) were commonly used throughout China. It is likely that the heat treatment techniques such as annealing and hot-forging spread across China in the Erligang Period with the casting technology. It is also likely that the use of high-tin bronze artifacts reflected the social hierarchy at the site of Yinxu. In addition, it is suggested that some bronze artifacts excavated from the sites of Yinxu and Dayongzhou, Xingan were probably quenched. After the Western Zhou Period, high-tin bronze were used all over China but the composition of the alloy varied between sites and between regions. In Huabei, bronze artifacts produced in the Shanxi province after Spring and Autumn Period contain amount of tin while the artifacts produced in the Henan region contain amount of lead. In Huazhong, bronze artifacts excavated in the lower Chang Jiang region contain amount of tin and lead while in the middle Chang Jiang region, the percentage of tin and lead in the bronze varies to a degree between tombs although high-tin bronze were generally predominant.

As for the heat-treatment techniques, this paper just follows the opinions of other authors. But it is necessary to reexamine the terminology and identification methods of heat-treatment techniques. The composition analysis also has some methodological problems. For example, the same samples were analyzed by different authors (e.g. Panlongcheng and No. 251 tomb of Jinshengcun) and these authors reached different results.

It is also likely that tin was variously used. Tin was probably used in order to joint metal parts and to coat the surface of the metal (Su et al. 1995: p.322; *He* 1988, 1991; Ma et al. 2007). Further studies are necessary to clarify the tin technology and reveal its historical developments during the Pre and Post Qin Periods.

### *Notes*

1. Nishimura reviewed heat treatments techniques chronologically by reference to recent composition analyses undertaken in China. He suggested that forging and annealing (*Tuihuo*) appeared earlier than quenching (*Cuihuo*) and tempering (*Huihuo*). This paper also follows his terminology.
2. Although Su Rongyu argued that Pre-Qin bronze artifacts were mostly produced by casting and rarely heat-treated, he also accepted that the techniques of annealing and quenching already existed in Pre-Qin Period (Su 1995: p. 279).
3. It is reported that an awl excavated from the site of Zhangying, Changping in Beijing, which is dated to the lower Xiajiadian Period, also contains 24.54% tin. However this is probably caused by surface erosion (Cui et al. 2007).

4. The composition analyses on bronze artifacts excavated from No. 160 tomb of Guojiazhuang, which is dated to Phase 3 of Yinxu Period, revealed that most of the vessels were made of high-tin bronze (IV S) while most of the weapons were made of high-lead bronze (Zhongguo Shehuikexueyuan Kaoguxueyanjiusuo 1998).
5. Unlike Nishimura (2000), Uchida translated *Cuihuo* as tempering.
6. It is reported in another paper that this engrave knife contains 28.6% tin (Gu et al. 2004).
7. As for the Shang Period, it is reported that 6 tin dagger axes and tin ingots were excavated from the site of Yinxu (Qiu et al. 1983). However, no formal reports have been published yet.
8. Among analyzed samples, welding material was excluded.
9. According to Zeng, the proportion of lead and tin was different between styles such as Zhongyuan style, Fangzhongyuan style, Wu style and Chu style.
10. He Tangkun argued that a Late Spring and Autumn bronze sword excavated from Yangjiashan, Changsha and Zganguo mirrors and sword were processed by quenching and tempering (He 1993).

Figure 1: Division of the tin lead bronze by Su Rongyu(Quoted from Su 1995: p. 186)

Figure 2: Histogram of the composition of bronze artifacts excavated from the site of Panlongcheng in the Hubei province (Hao et al. 2001)

サンプル数 : The number of samples
容器 : Vessels
工具和兵器 : Tools／Weapons

Figure 3: Histogram of the composition of bronze artifacts excavated from the site of Zhengzhou Shangcheng (Hao et al. 2001)

Figure 4: Histogram of the composition of bronze artifacts excavated from the tomb of Fu Hao in the site of Yinxu (Hao et al. 2001)

Figure 5 : Histogram of the compositionof bronze artifacts excavated from the west area of Xiaotun in Yinxu (Hao et al. 2001)

サンプル数 : The number of samples
容器 : Vessels
兵器和工具 : Weapons/Tools
残片 : Fragments
工具和其他器物 : Tools/Other artifacts

Figure 6: Analyses on a trim knife excavated from in Dayangzhou, Xinkan in the Jiangxi province

Microstructure of trim knife XDM383×50
Microstructure of trim knife XDM383×500
Trim knife XDM383 and same styled trim knife
Results of X-ray spectrometry

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# Micro-chemical Analysis on High-Tin Bronze Helmets Excavated from a Royal Tomb of Yinxu

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**[Abstract]**

A series of micro-chemical analysis was carried out on high-tin bronze helmets excavated from a Royal Tomb HPKM-1004 in the Yinxu. Two kinds of metallurgical textures, such as dendrite and homogeneous phase without phase boundary, observed which suggest a quenching technique and then followed by heat treatment process, probably tempering. Chemical analysis revealed that most of helmets were made of high-tin bronze and surrounded by tin-gilding layer. Result suggests that Yinxu's craftsmen purposely used different proportion of copper and tin to produce bronze objects according as function.

**[Key words]**

Yinxu, Bronze, Chemical composition, High-Tin, Gilding

## *1. Introduction*

Due to find the site of Oracle bones and tortoise carapaces with ancient inscriptions, the Institute of History and Philology, Academia Sinica launched a series of excavations in 1928 in the modern village of Xiaotun in the suburban of Anyang in the Henan Province. The excavations revealed large-scaled remains of Palaces and tombs. In 1934, the excavation work also started in the area of Xibeigang on the north bank of the Huang River because the area was seriously robbed repeatedly. As a result, 10 large tombs and one large unfinished tomb were discovered in this area. These tombs are cross-shaped. Each tomb consists of a rectangular main chamber at the depth of 10m and sloped corridors running from the main chamber towards four directions. Most of the tombs were looted and burial artifacts were mostly robbed. Although only fragments of the artifacts were discovered, their richness of artifacts and the large scale of the tombs strongly suggest that these tombs were royal tombs in the Shang Period.

The tomb of HPKM1004 was one of the large tombs discovered in the Xibeigang area. The main chamber is approximately 16m by 18m, 12m in depth. The lengths of sloped corridors are approximately 16m, 30m, 15m and 15m from North, South, East and West, respectively. Artifacts excavated from this tomb suggest that this tomb should be corresponded to the Yinxu Phase 2 and Phase 3 (Liang and Gao 1970). This tomb yielded *Ding* with an ox pattern, *Ding* with a deer motif. At least more than 100 bronze helmets (Fig. 1) and over 700 dagger-axes and spearheads were discovered from this tomb, many of the bronze helmets were fragmentary and unreconstructable though.

## *2. Helmets Excavated from the Tomb of HPKM1004*

The helmets from the HPKM1004 are very unique and characterized by the following reasons;

(1) No helmets were discovered in the other sites in Yinxu. Except the HPKM1004, only one helmet was discovered in the Yinxu Period sites from Taiyangzhou, Jiangxi Province in China.

(2) A tube is attached to the top of the helmet. The helmets from the HPKM1004 are very similar to those used in Central Asia, and Middle East in form which feathers were inserted into the tube.

(3) Some of the helmets are decorated with a *Taotie* pattern on the front face. Others are decorated with the whirl pattern on the side face. These patterns were traditionally used in the Yinxu Period.

(4) They are well-preserved and show blackish or silver surfaces rather than oxidized greenish in color.

The (1) and (2) suggest that this type of helmet was introduced from northern warriors in the northern China with other objects such as chariot ornaments. On the other hand, the (3) suggests that these helmets were produced in the Yinxu. In terms of making technique, the (4) indicates that the helmets are probably covered by a tin layer (Zhou 1957; Ma *et al.* 1999).

Artifacts from the palace and royal tombs are now stored at the Institute of History and Philology, Academia Sinica (Taipei). These artifacts are very important for understanding the casting technology in the Ancient China. In the 1970s, the first metallurgical investigation has been carried out on the helmets from the HPKM1004 (Wan 1970). However, the analysis method was not established well at that time and the helmets were not fully studied by the recent days. New series of metallurgical study launched with techniques of scanning electron microscope and X-ray analysis on fragments of bronze artifacts. A preliminary analyses on the helmets indicated that the surface of the helmet is covered with a thin tin layer, which is pointed out already (Fig. 2). Then 27 pieces from the helmets were selected for further detail investigation. This paper reports results from a series of investigation on the helmets from the HPKM1004 and discuss possible techniques of high-tin bronze in the Yinxu.

### *3. Studies Helmets from HPKM1004*

**(1) Helmet Types**

The helmets from the HPKM1004 have various size, shapes, and styles of design but can be divided into 6 types in terms of decoration; helmets with 3-different motifs (*Taotie*) of ox, sheep, and tiger, helmet with whirl pattern, helmets with Eyes pattern, and without decoration (Fig. 1). These contexts may suggest that these six types of the helmets were produced in different factories. Thus it is expected difference of chemical composition and metallurgical texture in bronze.

**(2)Parts of the Helmet**

A drawing of a representative helmet is shown in Fig.3-1. The width and height of the helmets are *ca.* 20cm and 26cm, respectively, and have a tube on the top. Including the tube, the helmet was cast together in the same casting mold. The samples were carefully selected from different parts of the helmet to try to investigate any difference in metallurgical texture and chemical composition.

### *4. Analytical procedure*

An electron microscopic technique is used for study of micro-metallurgical phases and their chemical analyses. All analytical procedure is carried out at the Laboratory of Electron Probe Micro-Analyses (EPMA Lab) in Institute of Earth Sciences, Academia Sinica.

**(1) Sample preparation**

To observe a section of bronze objects through the surface to the interior, the selected samples were sliced off in a small piece (less than few cm in size with few mm in thickness) by a micro-diamond saw. To avoid damage the original texture of the bronze during the cutting process, rotation speed of the diamond saw was operated in 100 r.p.m. with the distilled water for cooling. Cleaned samples by ethanol were mounted in a cold-mounting (room temperature cured for eight hours) epoxy resin with 1-inch diameter mold and exposed surfaces were well polished with Alumina paste.

**(2) Surface observation and chemical analysis by Scanning Electron Microscope (SEM) with an energy dispersive X-ray spectrometer (EDS)**

Micro-metallurgical texture of each polished sample was initially observed by an optical microscope with the reflection light. Then, a scanning electron microscope (SEM: JEOL JSM-6360LV) was used to observe micro-scale texture. Back-scattered electron image, which represents mean atomic abundance by contrast in back and white image, from the surface of the polished section. Analysis of the micro-metallurgical phases and their elemental abundances and mean chemical composition of bronze were measured by an energy dispersive spectrometer (EDS: Oxford Instruments Ltd., INCA-300) which equipped with SEM, used under the beam conditions of 15 kilo Volt (kV), and 180 pico Ampere (pA) for the acceleration voltage, respectively. Analyzed points were selected with the back-scattered electron images to avoid damaged and weathered areas.

Mean chemical compositions were determined in 10-areas of 120 $\mu$m x 90 $\mu$m (1,000 times in the magnification of SEM image for each 100 seconds, quantitatively. It is aiming to understand whole chemical value of bronze which suggests an initial mixture ratio of Cu (copper), Sn (tin), Pb (lead) in molten bronze. The quantitative data were normalized as metal compositions, using the X-ray intensities of pure metal standards, Cu, Sn, Pb and some others (PbS, Fe-Ni-Co standard alloy [NBS868], and so on). Analytical results from the 1200 $\mu$m x 900 $\mu$m area were compared with synthetic bronzes within 1% by weight, which chemical-known bronzes (Cu +Sn) and lead containing bronze (Cu + Sn + Pb) alloys, and confirmed EDS results were reliable to discussion.

**(3) Mapping and phase analysis of bronze metal phases by Wave-length Dispersive Spectrometers (WDS) with Electron Probe Micro-Analyzer (EPMA)**

The WDS has an advantage in comparison to the EDS because of their X-ray resolution. For examples, the EDS spectrum is not discriminate when the peaks of lead (Pb-M $\alpha$ ) and sulfur (S-K $\alpha$ ), or oxygen (O-K$\alpha$) and tin (Sn-K$\alpha$) because their peaks are interference each other, whereas the WDS performs their identification clearly. Thus the WDS is appropriate to study phase difference among metal, oxide and sulfide. To confirm the phases, qualitative analysis and elemental distribution mapping analyses were made by JEOL hyperprobe EPMA JXA-8500F with 25kV, 15nA, and focused beam for the acceleration voltage, beam current and beam size, respectively. The mapping is able to observe chemical heterogeneity in entire bronze, individual phases, and impurity (or trace elements).

## *5. The metallurgical Texture and their Chemical Compositions*

**(1) Bronze interior**

Representative back-scattered electron images (BEI) are shown from Figs. 3 to 5. Figs. 3 and 4 show the sections of ornamental parts of helmets and Fig. 5 shows the section of a tube on a helmet. The bronzes sized 2mm to 4mm in thickness in all samples. Main bodies (interior of bronze) of the samples are mostly well preserved and not affected by corrosion or oxidation from the surface. It seems that the main body has not been altered since the casting. The bronze textures classify in two types, such as (1) dendritic texture and (2) homogenized (non-textured) interior as well as chemistry. Figs. 3-2 and 3-4 are images of the sample of No. 0910 and typical dendrite are observed (Fig. 3-4), which represent the $\alpha$ phase (darker in contrast in the BEI) and the $\alpha + \delta$ phases (brighter in contrast BEI: Cu31Sn8) of bronze. The dendrite indicates quenching process during casting. In samples of No.0906 and No. 0903 (Fig.4), on the other hand, the dendrite is not observed and the whole texture is homogenized which is characterized a process of heat treatments (perhaps tempering) after casting.

Table 1 shows the mean value of chemical composition from the main bodies of studied 27 samples (Table 1). The Cu/[Cu+Sn] ratio (by weight) ranges between 0.78 and 0.86 and the concentration of tin ranges between 14 and 22 wt% (weight percent). In lead, 15 samples contain less than 1wt% and 6 samples contain from 1 to 3wt%. The maximum concentration of lead is 5.8wt%. Samples also contain other elements such as iron (Fe), sulfur (S), silver (Ag) and selenium (Se). These elements were identified as shared shape between the phase boundaries of bronze. Their sizes are several to 20 $\mu$m in diameter.

**(2) Surface Tin layers**

Figs. 3-3, 3-6 and 3-7 show the BEI of sample of No. 0921. This part was selected from the nose of the *Taotie* pattern of the helmet. The nose part is concave in shape and casting mold is still remained on the ventral surface of the sample (Fig. 3-3).

This sample shows darker layer with a thickness of 10$\mu$m to 20$\mu$m on the surface (Fig. 3-6). Fig. 5 shows BEI of the samples of R45803 and R45808 which are cross-sections of tubes of helmets. The images clearly show that there are dark surface layers on both of inner and outer surfaces of the tubes. The thickness of the layers ranges from 10 $\mu$m to 100$\mu$m.

Fig. 2 shows typical example of layered surface from sample No. 0701. Fig. 2 (bottom) shows elemental distributions of Cu and Sn with BEI. The BEI and Sn mapping clearly indicate a tin (Sn)-rich thin layer surrounds the dendrite bronze and its thickness is at least 100 µm. The maps also indicate that the Sn-rich layer near the surface does not contain Cu.

**(3) Other high-tin phases**

Other samples show that tin-rich phases penetrate into the main body from the surface with the dendritic structure. Fig. 6 shows an example from the sample of No. 0919. This sample has a complex texture with tin-rich phases. So that each phase was examines by spot analyses of EDS. Fig. 6 (right) shows analysis spots and their Cu/[Cu+Sn]ratios and the tin-rich phases in the sample consist of darker phases (P1 and P3) which is close to that of the $\varepsilon$ phase of Cu-Sn alloy (Cu6Sn5 :Cu/[Cu+Sn]=0.545) and phases (P2) which is close to that of $\eta$ phase (Cu3Sn: Cu/[Cu+Sn]=0.75).

## *6. Techniques of Bronze Casting and Tin-gilding*

**(1) High-Tin Bronze in the Main Bodies of the Helmets**

The Institute of Archaeology, Chinese Academy of Social Sciences reported chemical composition of the Yinxu Bronzes by the X-ray fluorescence analysis. The results showed that many of bronze vessels were made of high-tin Bronze and contain up to 5wt% lead (Zhao 2005). In the current study on Academia Sinica collection, most of vessels contain more than 15wt% and 2wt% of tin (at max. 23wt%) and lead (at max. 7wt%), respectively, of studies 50 bronze artifacts (Uchida & Iizuka in press), whereas the rest are type of arms and made of lower-tin bronze. In this study on helmets, 19 samples of 27 helmets (nearly 70%) show over 15 wt% tin (with 8 samples contain more than 17wt% tin) but less lead that 15 samples contain less than 1wt% Pb.

The lead is flux and lowers melting temperature and viscosity of bronze during casting. It is well known, however, that the high-Pb bronze is brittle than lead-free bronze. To add tin affect to lower melting temperature of bronze as well, but it makes bronze harder. Bronze vessels are usually complex-shaped and have decorated surface. Thus the low viscosity of the melt is required for casting into the vessels' mold, which is fine complex carved pottery. In addition, vessels do not need to be hard for their purpose of usage. In contrast, helmets might be required hardness because it is arms. Therefore, tin was intentionally added, but less lead, for the helmets. Although some of the samples include small amounts of lead, this might have been caused by conventional method of craftsmen in the Yinxu.

Excluding the helmets and the vessels, the high-tin Bronze is observed in chariot belongings. A bow-shaped implement (R6919) from the HPKM-1003 (Yinxu Phase-3) shows that the Cu/[Cu+Sn] ratios and concentrations of tin are 0.818, and 17.1 wt%, as mean values, respectively (Uchida & Iizuka, in press). And another bow-shaped implement from a chariot pit (Yinxu Phase-4) is also made of high-tin (18 wt% Sn). (Zhao 2005). It is widely believed that the chariot cultures were derived from northern warriors in China. Thus, high-tin bronze technology might be innovated from the different culture such as the northern warriors.

**(2) Tin-rich Layer on the Surface**

Lian Haibing analyzed a bronze sword with a tin-rich layer on its surface which made during the Warring State Period (BC 5th century) (Lian 2000). According to her investigation, if the causative agent for corrosion penetrates into the main body beyond the tin-rich layer on the surface, the corrosion phases are created in the main body without alteration of the dendritic texture in the main body. At the same time, pure copper is segregated as a result of chemical reaction. A few of samples in this study also show such pure copper phase (Fig. 7). As for these samples, the tin-rich phases might be formed by reaction of corrosion.

Some other investigations suggest that even in the case of the bronze artifact with low concentration of tin near the surface, copper can be segregated and tin-rich phases appears as a result of corrosion (Xiao et al. 20004). However Ma Qinglin investigated that $\varepsilon$ and $\eta$ phases (see Fig. 6) are not able to observe in the pseudo tin-rich phases caused by corrosion (Ma et. al. 2000).

In this study, some samples show that tin-rich phases penetrate into the main body keeping the dendritic structures. However, the samples have highly concentrated oxidized tin phases similar to $\varepsilon$ and $\eta$ phases, and pure copper grains were not observed. Furthermore, except the helmets, the surface tin-rich layer was not observed from the bronze artifacts in the Yinxu. These facts strongly suggest that the helmets from the HPKM1004 were artificially gilded by tin.

A common method of tin-gilding is to soak bronze into melted tin. It is noteworthy that the inside of the tube of the helmet is also covered with a tin-rich layer. Observation of cracks on the helmets (these cracks might be created during casting) also revealed that both of the ventral and dorsal surfaces of the helmet were covered with a tin-rich layer. These facts suggest that the tin-gilding was undertaken exactly after the casting. As for the sample No. 0921 (Fig.3-7), fragments of the casting mold (silicate minerals) are still remained on the inner wall of the bronze piece and a tin layer was observed between the mold and bronze. It seems that melted tin penetrated into this boundary layer during gilding process. Some studies undertook some experiments and reported that the $\varepsilon$ and $\eta$ phases were created in the tin-layer and thin tin layer containing small amounts of copper was created on the surface when this method was used (Ma et al. 2000). Consequently it is concluded that the helmets from the HPKM1004 might be processed by tin gilding after casting.

**(3) Heating Treatments after Tin gilding**

The homogeneous texture of main body of some of the helmets suggests that they were heat treated after casting. The texture also shows that the tin-gilding layers were also heat-treated and became unclear of the dendrite as well as texture of main body (Fig.4). This suggests the heat treatments (perhaps tempering) were probably undertaken after the tin-gilding.

Unlike the high-tin Bronze artifacts produced after the 5th century, which were repeatedly processed with heating and forging, the samples did not show any evidence of hot-forging. It is likely that the technique of forging were not established yet in the Yinxu Period.

### *7. Concluding remarks*

The helmets are very unique objects because of their tube on the top and slightly tall in shape. And the helmets are only yielded from the HPKM1004 in the Yinxu. Since their form is similar to helmets which used in Central Asia, and Middle East, it is very likely that this type of helmet was introduced into China probably by northern warriors together with chariots ornament and arms in the Yinxu Period. The main bodies of the helmets contain highly amounts of tin. It is distinguished that the average of Cu/[Cu+Sn] ratio of the helmets is 0.838, and the concentration of tin in helmets is quite high that 8 samples contain more than 17wt% in Sn/[Cu+Sn] ratios. The bronze vessels in the Yinxu were also often made of high-tin bronze, the other artifacts are not made of such high-tin though. Since most of the helmets from the HPKM1004 were made of high-tin bronze, it seems that the craftsmen of Bronze in the Yinxu have already understood the physical properties of bronze and adjusted the proportion of copper and tin according as function. Excluding the Helmets, no bronze artifacts from the Yinxu were finished with the tin-gilding. Thus it is suggested that the gilding technique were probably introduced from the out of the Yinxu.

The high-tin bronze were already used for the bronze vessels in the Yinxu Phase 1 of the Late Shang Period. It suggests that the technology of high-tin bronze has already been in the Yinxu before the helmets. The helmets vary in pattern and shape and are also decorated with a *Taotie* and whirl pattern, which are characteristic patterns in the Yinxu. These indicate that the high-tin bronze helmets were produced by local craftsmen in the Yinxu. And they also applied new technology of tin-gilding for the helmets.

The high-tin Bronze is unique objects in Asia. In China, the high-tin Bronze was firstly produced in the Late Shang Period (Shimizu 2009). The helmets from the HPKM1004 are made of high-tin Bronze. The helmets were also applied with new technique of the tin-gilding which probably introduced from the northern warriors in the northern China. The helmets are important objects to understand the early stage of the spread of high-tin Bronze technology over Asia.

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## High-Tin Bronzes in the Korean Peninsula before Unified Silla

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***1. Beginning of bronze and its development***

The emergence of bronze in the Korean Peninsula has been commonly dated around the 5th- 4th century BC, but more detailed research is necessary because of the possibility of earlier dates for the oldest bronze according to the renewed chronology of the Yayoi period, which is now dated earlier. The oldest bronze artifacts were related to those in the Liaoning region, such as Liaoning bronze daggers and the bronze mirrors with rough geometic patterns. When a great number of narrow bronze swords were manufactured in the Korean Peninsula, bronze artifacts became more varied, and the bronze production technology was developed further, leading to the emergence of the bronze mirrors with multiple string attachment loops, decorated with finely ridged line patterns.

During the first half of the Three Kingdoms period (1st to 3rd century AD), the large-scale production of iron tools was common, while the evidence for the use of bronze tools rapidly declined. Bronze artifacts in grave goods were replaced with iron ones. The production of bronze was small-scale, and the bronze artifacts appeared as daggers, imitative mirrors, harnesses, belt hooks, or bronze pot which may not have been used as daily tools. This may indicate that bronze was mainly used as ritual, burial goods, which represent high social status. The excavations of the graves in the Lelang Commandery yielded various bronze artifacts, but their number is small in the South central part of the Korean Peninsula. Bronze belt hooks and harnesses, recovered in the wooden chamber tombs of the 2nd to 3rd century AD, need to be systematically examined.

In the 5th century, a large number of various bronze artifacts were buried in the tombs in the Goguryeo and Silla regions. Notably, the tombs in Silla yielded bronze pot, bronze pot with handle, and bronze bowl with cover with many types, which suggest the interaction with Goguryeo. The excavations of the tombs in the Gaya region recovered bronze and gilt bronze wares, which may have been trade goods or gifts from the higher social status.

After the 6th century, towards the period of Silla, the number of bronze artifacts in tombs sharply declined, while the daily bronze tools appeared in settlements. The 8th and 9th centuries saw the large-scale production and the trade of bronze wares. In particular, 聖徳大王神種 in the 8th century shows remarkably high skills that mark the apex of the bronze casting technology.

The interaction with China added a great variety to the ancient casting technology and its archaeological evidence, as indicated by the various bronze artifacts in the tombs after the 5th century. However, we have too few samples of high-tin bronze, characterized by the high inclusion of tin, to make detailed descriptions and comparisons. The future research should enable us to distinguish between imported and local products and to clarify the technological development of bronze artifacts.

***2. Recent research on high-tin bronze***

Research on the bronze production technology in Korea has been increasing under great interests from researchers since 2000. The studies on the production technology and the composition analysis have been developed as a result of the comprehensive research on the bronze mirrors with multiple string attachment loops, decorated with finely ridged line patterns (崇実大, 2009). More recently, the analysis of the micro-structure of the bronze mirrors from 忠南論山市院北里 suggests that the mirrors contain ca. 30% of tin and a small amount of lead. The high inclusion of tin was probably intended to facilitate the fine decoration and the adjustment of color (兪在恩・趙詳紀・朴長植, 2010, 銅陵青銅器文明シンポジウム, 中国科学技術大学, 日本文化財学会第27回大会, 2010).

The analysis of lead isotope ratios was conducted by two institutes under the project of “Composition analyses of the bronze artifacts of the Three Kingdoms period, using lead isotopes” (国立中央博物館・日本歴史民俗博物館, 2009). This study aimed at the compositional identification of bronze artifacts. It allows us to examine whether multiple bronze fragments belong to a single piece. However, we need further studies and comparative specimens to obtain more information.

The ongoing project “The production technology of high-tin bronze” has been investigating the earliest evidence for the forging technology. The study by 清水康二 (2009) on the earliest date for the Yugi (binary high-tin bronze) in Korea still needs more evidence. I would suggest the analysis of the high-tin bronze samples of the 5th-9th century.

Recently, 李在城( 2010.6) complied the analytical results of 160 high-tin bronzes (Bancha Yugi) and suggested that rivets of Cu−Ag alloy were used at an attachment between the body and the stand of bronze bowls in the Goryeo period. The comparative study of bronze spoons with experiments indicates that the bronze production with a hammering technique has existed since the Goryeo period (918-1392) to the present. In addition, the study clarified that the use of salt water during the hardening process had a role to facilitate the removal of oxidized surface.

The following describes the bronze wares from the southern Korean Peninsula to overview the development of bronze technology and the analyses of artifacts.

### *3. Bronze wares of the Three Kingdoms period in the southern Korean Peninsula*

#### 1) Bronze wares in the Silla region

A large number of bronze wares have been recovered in the Silla and Gaya tombs. Bronze pot from the wooden chambered tombs in the 3rd century includes those from Ulsan Hade sites, Kimhae Yangdong, and Daesungdong sites. These pieces must have been imported from China or the northern area although researchers have various ideas on trades.

Recently, Hyun-hee Kim (2009) conducted a typological analysis of 79 bronze bows from the Silla tombs in the Gyeongju area to examine the customs of burial goods.

Hyun-hee Kim subdivided bronze pots into two types with and without a lid. Bronze pots with handle were divided into a jar type and a disc type. Bronze iron were classified into short and long types. Bronze bowl with cover were divided on the basis of the various shapes of handles, such as loop, sphere, shape with lotus flower, bird, and cross. Moreover, the observation of a textile attached to bronze artifacts allowed him to suggest that bronze tools were wrapped with a textile, which may have signified the possession of bronze tools as burial goods.

The shapes with lotus flower and the shape of a flower with eight leaves in the handle of the bronze bowl with cover from Silla represent the Buddhist decoration. They are observable in the artifacts of the 5th century and should have been imported motifs. This requires us to examine whether the bronze artifacts from the Silla tombs in the 5th century were produced in Silla or imported from Goguryeo or China. This question can be effectively answered by the accumulation of composition analyses, which should be led by the National Museum of Korea where the relevant samples are stored. In addition to bronze, the analyses of organic materials in lacquer artifacts can help us clarify the ancient trades, but such studies are still in the initial stage (岡田文男・李恩碩・林志暎 2009).[1)]

Remarkably, a single bronze mirror, probably made in the late 3rd century, was recovered at Hwangnamdaechong(皇南大塚)southern tomb, which also yielded gold and silver wares and bronze wares. We have a very few examples of bronze mirrors buried in the Silla tombs. We also have little evidence for the production of TLV imitative mirrors during the 5th century in the Korean Peninsula. This suggests that the bronze mirror of Hwangnamdaechong(皇南大塚) was imported from the northern area or Japan[2)]. The interaction with the northern china brought various metal and glass wares, while cone shells from Okinawa and artifacts of white birch bark were imported into the Silla region. Despite the hostile relationship between the Silla and Wa, there were exchanges of messengers and hostages, which should have included some trade items. Whether the mirror came from China or Wa (or from China through Wa) can be effectively examined by the composition analysis in comparison with Japanese bronze mirrors.

#### 2) Bronze wares in the Gaya region

Since the Proto-Three Kingdom period (1st to 3rd century), Six Gaya in the Gyeongsangnam-do area formed a close relationship with Silla. This resulted in the occasional recovery of exotic items in the tombs after the 4th century. Such examples include the glass cup from Okjeun(玉田) tomb, which may have been imported from Silla. Notably, some researchers suggest that bronze plate and bowls were imported from Southern Court (権五栄 2010). It is unclear whether this bronze ware was modified in Baekje or directly imported from Southern Court, but the influence from the latter area is proposed.

However, we still do not know the exact relationship with Southern Court. It is significant that the bronze artifacts from the Silla tombs were derived from the northern areas, while those of Gaya were originated in Southern Court.

The bronze wares in Gaya has round bases with inverting rims, which contrast to flat bases with everting or straight rims of the Silla bronze wares. The pieces from Goryeong Jisandong tomb No.44, Jinju Sujeongbong tomb No. 2, and Uiryeong Kyoungsanri tomb No. 2 can signify the relationship with Baekje rather than the direct relationship with Southern Court.

**3) Bronze wares in the Baekje region**

The typical bronze wares from the Baekje region include pots with handle from Pungnab Earthen Wall and bronze wares from Tomb of Muryeong in Gongju. Another example from Mireuksaji temple site(弥勒寺址) was analyzed in the early 1990s.

鄭光龍 (1992) analyzed two pieces of large bowls, a round-based jar, and four pieces of plates, suggesting that these artifacts were high-tin products that were casted and cooled slowly. The products include 18.6%, 21.1%, 19.8%, and 20.3% of tin and 0.38%, 0.12%, 0.45% of lead.

The bronze wares from Tomb of Muryeong include one jar, three plates, three bowls, and five-cup which appear to show the types identified in those from the 大伽耶 region[3]. Among those, a jar contained one bronze spoon and reportedly shows hammered traces after casting. The wall and the rim of the jar are inverting with a round base, resembling those from the Gaya tombs. The bowls show two types, and two pieces with everting rims have stands that suggest a link to Silla. The plates are low with flat bases, as exemplified by those from 池山洞 in Goryeo.

If the bronze wares of Tomb of Muryeong (AD 525 and 529) were imported from Southern Court, instead of the products in Baekje, the morphologically similar finds from Gaya should be roughly contemporaneous and also imported items.

**4) Bronze wares in the Silla period**

The above provided an overview of bronze wares from Baekje, Silla, and Gaya around the 5th century. From the mid 6th century to the Silla period (AD 676-935), we know various bronze wares, but their scientific study, such as composition analysis, was not common. There was little interest in high-tin bronzes among researchers, and the establishment of the chronology has been hindered due to the recovery of relevant finds from settlements instead of tombs.

The initial analysis on the bronze wares from the Silla period was done by Professor 崔炷 (1983). The examination of five pieces of plates and bowls from Anapji Pond suggests that the pieces that were casted and hardened were high-tin bronze with 23.2% and 22.5% of tin inclusion, while those that were casted and annealed included 15.2%-17.5% of tin. The bronze wares from the Silla 王京 region and Bunhwangsa temple site(芬皇寺, 7th-9th century AD) include the casted and hardened products with 19.2%, 21.5%, 20.3%, and 21.9% of tin, while the casted and annealed products contained 14.6% of tin. 朴長植 (2004) analyzed two pieces of bronze wares from Icheun Sulbong Mountain fortress(利川雪峰山城) in Gyeonggi-do (from the Three Kingdoms to the Silla period), suggesting that they were forged and hardened with 22.3% of tin.

Gaya National Research Institute of Cultural Heritage (国立加耶文化財研究所)has been investigating the iron and bronze wares from Haman Sungsan Fortress (from the mid 6th to the 9th century). Significant results should be obtained by analyzing the composition and production technology of the bronze wares of the 8-9th century.

Among them, 14 fragments, including rims, bases, and plates, are under analyses, and we obtained interesting results for two base fragments of bowls, one rim fragment, and one plate, which were recovered in the layer of the 8-9th century[4].

The analyzed four pieces are composed of pure, smelt copper and tin. They were found to have been hardened. Despite the absence of hammering, they were probably manufactured with a technique precursory of the Bancha (Yugi) technology or with an initial Bancha technology.

In addition, a soapstone cast for bronze spoons was excavated around 芬皇寺 in Gyeongju. This find should allow us to examine whether bronze in the Silla period was made by casting with subsequent hardening and hammering.

***4. Summary***

The above provided an overview of the bronze artifacts recovered in the southern Korean Peninsula and described some studies. The results of the analyses to date indicate that the bronze production before the Silla period (AD 676-935) did not employ a hardening technique with hammering. However, the bronze artifacts from the Silla period suggest that the production of high-tin bronze (Yugi) had started during this period at the latest. The recent rapid increase in the study of high-tin bronzes in Korea has prompted their analyses and the studies on the technological development. The future progress of the comprehensive and multi-disciplinary research should shed more light on the high-tin bronzes in the ancient Korean Peninsula.

I am grateful to the following individuals for their kind supports. Some provided me with relevant literatures.
金昡希，朴長植，朴種益，朴允禎，兪在恩，李在城(敬称略)

1) The results of the analysis of the lacquer wares from 慶州皇南大塚 suggest that the they were buried as grave goods after use. The lacquer wares may have been imported from China or produced in Korean Peninsula with a high production skill invented in the period of Han Dynasty in China. The lacquer ware was found to have been placed in the bronze steamer. If the high quality lacquer wares were imported from China, the most of the bronze wares from the Silla tombs in the 5th century should also have been imports. According to the inscription (乙卯年國岡上廣開土地好太王壺杅十) on the bronze bowl with cover from Houchong tomb, this product in Goguryeo was imported to Silla. This in turn suggests that the bronze wares of the same period must have been imported from Goguryeo.
2) One probable idea is that they were imported from Wa or the Southern and Northern Dynasties (see the paper by 高久健二 and 上野祥史).
National Museum of Japanese History, 2002,『The Interaction between Wa and Gaya in Acient Eastern Asia』, The 5th Rekihaku International Symposium.
3) 李漢祥, 1994,「武寧王陵出土品追報 (2)」『考古学誌』第 6 輯
4) The analysis is conducted by Professor 朴長植 . The results to be published in an academic journal are briefly summarized here.

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崔炷・キムスチョル，1983，「統一新羅時代の容器に対する金属学的考察」『美術資料』第 32 号，国立中央博物館

Table 1: Typological classification of bronze wares from the Gyeongju area (金昡希 2009)

# High-tin bronze artefacts recovered from the tumuli in Gyeongnam in the Goryeo and Joseon periods.

Yong-Min Sin and Sang-Yong Lee[1)]
(Foundation of East Asia Cultural Properties Institute)

## *I. Intoroduction*

In South Korea, bowls and spoons are typical among high-tin bronze artefacts recovered from the tumuli in the Goryeo and Joseon periods. Up to now these artefacts have not sufficiently been studied in spite of the fact that they are the tools which directly reflect past dietary practices. In fact, the archaeological studies of high-tin bronze spoons have progressed very slowly[2)] and those of bronze bowls began only recently[3)]. Most references to them are limited to the brief descriptions in excavation reports. At the present, study of their manufacturing method, analysis of their chemical composition and ethnographical study are main issues of these high-tin bronze artefacts and archaeological studies such as the analysis of typological sequences of the artifacts are still at a primary stage.

This paper will discuss the typological features of the bronze bowls and spoons as well as their chronological changes. These artefacts are suitable for archaeological analysis of typological attributes because of their abundances and well-preserved condition among various types of high-tin bronze artefacts recovered from the tumuli in Gyeongnam in the Goryeo and Joseon periods[4)].

## *II. Terminology and typology of bronze artefacts*

### 1. Terminology of bronze bowls and spoons

It is confusing that the terminology of high-tin bronze artefacts is not standardized between different excavation reports and articles. Thus, the terms used to describe bronze bowls and spoons must be defined in this paper as below.

#### 1) Bronze bowls

Bronze bowls are usually divided into lidded bowls and lidless bowls (or lidded bowls with a stand and lidless bowls with a stand) depending on the presence or absence of a lid. “Bronze bowl” mentioned in this paper includes all of them. To mention each part of the bowls the terminology usually used for porcelain, as shown in Figure 1, can be used in order to avoid confusion.

#### 2) Bronze spoons

The terminology for the bronze spoons has already been suggested by Bae Yong-Dong et al.[5)] and also by ourselves.

### 2. Typology and typological transformations of the bronze artefacts

#### 1) Bronze bowls

Sixty-three bronze bowls in Gyeongnam were examined according to the classificatory criteria shown in Table 1. They belong to the Goryeo (18 specimens) and the Joseon (45 specimens) periods. For the typological classification, their form and the presence/absence of a lid were excluded from the classificatory criteria because they are not likely to be adequate criteria for the classification. The first priority must be given to the typological attributes which may demonstrate chronological changes. The result of the examination shows chronological changes in the height of the stands[6)], the profile of the rims and the method by which the stands were attached. The chronological changes of the bronze bowls according to this typological classification can be understood as follows.

##### (1) Height of stands

Table 2 demonstrates the average height of the bronze bowls and of their stands in the Goryeo and the Joseon periods. In the Goryeo period the average height of the stands is 1.12cm and that of the whole bowls is 8.76cm. The height of the stands does not exceed 1.5cm and neither does the whole bowl exceed 10cm. On the other hand, in the Joseon period, they are 2.21cm for the stands and 10.46cm for the whole bowls. This suggests that both the height of the bowls and that of their stand became higher through the transition from the Goryeo to the Joseon.

##### (2) Profile of rims

Table 3 shows the number of bronze bowls with each type of a rim profile. Except for one bowl which lacks a rim due to breakage, all 63 bowls were examined. A flared rim is a dominant type in the Goryeo period, accounting for 67% (12 specimens), followed by an incurved rim, 28% (15 specimens), and then a vertical rim, 5% (1 specimen). On the other hand, in the Josen period an incurved rim accounts for 57% (27 specimens), a flared rim 25% (11 specimens) and a vertical rim 18% (8 specimens). This demonstrates that through the transition from the Goryeo to the Joseon the number of a flared rim decreased while that of an incurved rim and of a vertical rim increased. It is known that a vertical rim appears in the late Goryeo period and is regarded as an indicator for the transition to Joseon period (Goryeo grave num. 9 of Deokcheon-Dong in Busan). These chronological changes must be related to the use of the bowls with a lid. It is supposed that the increase of incurved and vertical rims is due to the functional demand that the bowls need to sustain their lid. The bronze bowls with a lid became more popular through the transition from the Goryeo to the Joseon and this is probably related to the change in the dietary practice at that time. It is clear that these varieties of vessel shapes mean transformations reflecting the periodical aspects.

**(3) The method to attach the stands**

Table 4 demonstrates the number of bowls to which a stand was attached by each method in the Goryeo and the Joseon periods. In the Goryeo period the bowls without a stand account for 28% (5 specimens) and the bowls with a stand which was separately cast and later attached to the body account for 78% (13 specimens). The bowls of which the body and the stand were cast together are not involved. In contrast, in the Joseon period the bowls without a stand account for 31% (14 specimens), the bowls with a stand that was attached later account for 33% (15 specimens) and the bowls with a stand that was cast together with the body are 36% (16 specimens). The number of the bowls with a separately cast stand decrease in the Joseon and all three types were equally found. This fact can be interpreted as the development of casting technology in the Joseon period and it is necessary in the future study to investigate the manufacturing places of these bronze bowls and their typological features seen in their acceptance and supply.

**(4) Transformation of bronze bowls in the Goryeo and the Joseon periods**

To summarize, the bowls without a stand and the bowls with a separately cast stand are dominant in the Goryeo period while these two types and the bowls with a stand cast with a body are equally present in the Joseon period (Table 5). Thus, most distinctive attributes that reflect the chronological differences are the height of the bowls and of the stands, the profiles of the rim, and the technique to shape the stand.

**2) Bronze spoons**[7)]

First typological priority given to the bronze spoons is curvature of their handles and the shape of the end of the handle because it is believed that both features well reflect chronological differences. The former can be classified by the degree of curvature and the latter can roughly be divided into four types: swallow-tailed, semicircular, lotus and spatular. In the Joseoun period, the periodical changes can be observed in the swallow-tailed and the semicircular types. On the other hand, the lotus and the spatular ones demonstrate neither obvious variations nor chronological changes in their forms and thus are excluded from the discussion in this paper.

Except for the bronze spoons of which the end of the handles are missing, the total of 160 specimens recovered from the above mentioned sites were examined. According to the degree of the curvature of their handles they can be classified into type I to IV. To measure the degree of curvature the spoons were placed on a flat table with their both ends attached on the table and the height of the spoons were measured.

**(1) The changes in the degree of curvature and the ratio of the length of bowls to the whole length of the spoons**

Table 7 shows the degree of curvature and the ratio of the length of bowls to the whole length of the spoons by period in the Goryeo and Joseon. It demonstrates that the degree of curvature is more than 2.2cm and the ratio of the length of bowls to the whole length is more than 1 to 3 in the Goryeo period (Type I). The curvature is large and the bowls are small in general. On the other hand, in the Joseon period (Types II to IV) the degree of curvature is less than 2cm and the ratio of the length is less than 1 to 2.9. The curvature is smaller and the proportion of the bowls is larger than those in the Goryeo period.

Average measurement of these two features indicates that the both the degree of curvature and the ratio of the length of bowls to the whole length decreased through time from the Type I ($12^{th}$ to $14^{th}$ centuries) to the Type IV ($18^{th}$ century), although the both increased slightly in the Type IV (Table 8).

**(2) Comparison of the other dimensions of the bronze spoons in the Goryeo and the Joseon periods**

The results of the examination are summarized in Table 9. They can be interpreted as follows.

Firstly, for the depth of the bowls, the average is 0.41cm in the Goryeo period. On the other hand, it is 0.61cm in the Joseon period, increasing 0.2cm. It means the increment of the volume of the bowl by 50%, which is quite a large difference since this make it possible to scoop much more food with a deeper spoon.

Secondly, for the length of the bowls, the average is 7.5cm in the Goryeo period. On the other hand, it is 9.55cm in the Joseon period, extending about 2cm. It increases by 27% and would also reflect the increment of the volume of a bowl.

Additionally, for the whole length of the spoons, the average is 24.58cm in the Goryeo period. On the other hand, it is 25.8cm in the Joseon period, extending about 1cm. This change must be caused as the bowl of the spoons became larger.

To summarize, the dimension of the spoons, such as the depth and the length of the bowls and their whole length, as well as the curvature of their handle, are major typological attributes which reflect the chronological differences.

### *III. Chronology of the high-tin bronze artefacts*[8)]

The high-tin bronze artefacts buried as a funeral goods together with the celadon dated to the 12th to 14th centuries are regarded as the product in the Goryeo period. Among them the bronze bowls have a stand that do not exceed 1.5cm in height and have an incurved or a flared rim. In the transitional period from the Goryeo to the Joseon in the 14th century, a transitional type of bronze bowls that have a vertical rim appeared. All the bowls recovered from this period have a separately cast stand and this suggests that the stand and body of the bowls were never cast together in the Goryeo period.

Many bronze spoons share common characteristics in the Goreyo period. For example, the bronze spoons recovered from the graves nos. 2 and 4 of the Deokcheon-Dong ruins in Gupo, which are dated to the 12th to 14th centuries, and those from the graves nos. 1 and 2 of Gwisan-Dong in Changwon, which are dated to the middle-to-late 14th century, show less typological variations, all having a distinctive “ ∽ ”- shaped profile, a handle which is decorated with bamboo comb patterns towards its end, and a swallow-tailed handle end. On the other hand, the degree of curvature of the bronze spoons recovered from the grave no. 3 of Gwisan-Dong in Changwon is remarkably small and different from other spoons mentioned above in spite of the fact that they were recovered with the bronze bowls and celadon plates dated to the late 14th century. Their profiles are “∽”-shaped or slightly curving and can be regarded as a transitional type from the Goryeo to the Joseon.

In the Joseon period, the bronze artefacts were buried with Buncheong ware and white porcelain dated to the 15th to 18th centuries. The first chronological change can be seen in the transition from the Goryeo to the Joseon in the forms and the typological attributes of the bronze bowls which show wide variations. The stands are at least 1.5cm higher than those in the Goryeo period, an inclined, flare and vertical rims are equally present and the bowls with a stand which were cast together with the body newly appears. The typology of the bronze spoons radically changed from one period to another, showing distinctive differences. The most remarkable change is seen in the decrease in the degree of curvature of their handle and the increase in the dimension of the bowls. In addition, the end of the handles became simple without any decorations. It seems to show simplification of the bronze spoons when compared with those in the Goryeo period. The form of the end of their handle becomes suitable for their utilitarian use. A semicircular form increases while a swallow-tailed shape decreases and diminishes completely in the 16th century.

### *IV. Conclusion*

As discussed above, this paper has examined the changing aspects and the chronology of the bronze artefacts recovered from the tumuli in Gyeongnam through the Goryeo and the Joseon periods. The bronze artefacts in the Goryeo period were recovered with celadon which is dated to the 12th to 14th centuries. For the bronze bowls, their stand does not exceed 1.5 cm in height and their rim is either incurved or flared. A vertical rim appears as a transitional type in the transition from the Goryeo to the Joseon in the 14th century. The stand and the body of the bowls were always cast separately and then connected to each other. Bowls with a stand cast together with their body seem to be absent in the Goryeo period. While there were very few variations among the bronze spoons in the Goryeo period, radical changes occurred in the

Joseon period, Especially, the decrease of curvature of the handles and the enlargement of the bowls are remarkable changes. Also the end of the handles was sometimes decorated to new types of forms. It is supposed that these changes were mainly due to the changes in dietary activities caused by the religious beliefs and the development of agriculture in the transitional period from the Goryeo to the Joseon. This study, by using the chronology of porcelain recovered with bronze artifacts, focused on the observation of periodical changes in the typological attributes of bronze artefacts and the establishment of their chronology in the Goryeo and the Joseon periods, which had not been sufficiently known. Based on this, further studies which involve scientific analyses, such as metallographic observations and the study of traditional manufacturing technique of bronze artifacts, will progress the study of high-tin bronze artefacts in South Korea.

***Notes***

1) Chairman and Researcher, Foundation of East Asia Cultural Properties Institute.

2) For example, the following references are present.

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Sang-Yong Lee, Study on Bronze-spoon Excavated in burials of Gyeongnam Province between Goryeo and Joseon Dynasty. In: Research of Technology Producing Korean High-tin Bronze Ware. 2009.

3) Jagyeong Gu, Study on bronzeware excavated in burials at Yongnam Province between last Gorye and early Joseon Dynasty. MA Thesis submitted to Dong-A University, 2010.

4) Museum of Dong-A University, Burials in Deoksan-Ri, Gimhae. 1995.

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_________ Cultural site in Deokpo and Yigok, Geojae. 2008. (The excavation report of cultural relics in the section of new bypass road to be substituted from national road in Geoje)

_________ Joseon Dynasty Burials Gwuisan-dong, Changwon. 2008. (Historic site in access road section of Machang Grand Bridge at Changwon Gwisan-Dong Joseon Bunmyo (grave mound) at Changwon)

_________ Complex Cultural Site in Gaeum, Changwon (Second). 2009. (The excavation report of cultural relics in the site formation project area of Gaeumjeong-Dong in Changwon)

_________ Jukgok-ri Historic Site at Gimhae II (First and Second). 2010. (Historic site in Gimhae Gyeongjeon line -Busan new port railroad construction section/ Jukgok-Ri historic site at Gimhae)

5) The detailed terminology proposed by Bae Yong-Dong et al. is as follows. Large flat part to scoop food is termed “bowl ( 술 입 )”, a handling part is termed “handle ( 술자루 )”, an end of bowl is termed “edge ( 술날 )” and a part between the edge and the handle is termed “neck ( 술목 )”.

6) Jagyeong Gu, A Study on bronze ware excavated in the burials at Yongnam Province between last Goryeo and early Joseon Dynasty. MA Thesis submitted to Dong-A University, 2010, p. 34.

For the height of the stands, two types were identified depending on their forms. Nevertheless, their chronological variations were not considered.

7) The examinations of the bronze spoons have already been published in the following paper.

Sang-Yong Lee, A Study on Bronze-spoon Excavated in the Burials of Gyeongnam Province between Goryeo and Joseon Dynasty. In: Research of Technology Producing Korean High-tin Bronze Ware. 2009.

8) The chronologies of celadon in Goryeo period, and Buncheong ware and white porcelain in Joseon period are based on the following references.

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Figure 1. Names of each part of a bronze bowl. Lid, rim, rim, bowl, base and stand (from the top).

Figure 2. Names of each part of a bronze spoon. Bowl, handle, end of handle, edge, and neck of bowl (from the top left).

Figure 3. Table showing the chronology of the bronze artefacts. Period, date, bronze bowl, bronze spoon, contemporary artefacts, Goryeo, 12, Goryeo grave no. 33 of Jukgok-ri, Goryeo grave no.4-2 of Deokcheon-Dong, Goryeo grave no. 4 of Deokcheon-Dong, Goryeo grave no. 33 of Jukgok-Ri, 13, grave no. 33 of Jukgok-Ri, Goryeo grave no. 5 of Gaeumjeong, Goryeo grave no. 1 of Deokcheon-Dong, Goryeo grave no. 4 of Jukgok-Ri, Goryeo grave no. 2 of Deokcheon-Dong, Goryeo grave no. 1 of Deokcheon-Dong, Goryeo grave no. 9 of Deokcheon-Dong, Goryeo grave no. 2 of Gaeumjeong, Goryeo grave no. 2 of Gwisan-Dong, Goryeo grave no. 2 of Gaeumjeong, Goryeo grave no. 9 of Deokcheon-Dong, Goryeo grave no. 3 of Gwisan-Dong, Joseon grave no. 64 of Gaeumjeong, Joseon grave no. 67 of Gaeumjeong, Joseon grave no. 3 of Gaeumjeong, Joseon grave no. 41 of Gaeumjeong, Joseon grave no. 70 of Gaeumjeong, Joseon grave no. 2 of Gaeumjeong, Joseon grave no. 30 of Gwisan-Dong, Joseon grave no. 51 of Gaeumjeong, Joseon grave no. 37 of Gwisan-Dong, Joseon grave no. 79 of Gaeumjeong, Joseon grave no. 41 of Gaeumjeong, grave no. 12 of Jangpyeong, Joseon grave no. 64 of Gwisan-Dong, Goryeo grave no. 24 of Deokcheon-Dong, Joseon grave no. 3 of Gwisan-Dong, Joseon grave no. 13 of Gaeumjeong, Joseon grave no. 38 of Gaeumjeong, Joseon grave no. 91 of Jukgok-Ri, Joseon grave no. 70 of Gaeumjeong, no. 74 of Gangok in Geoje, Joseon grave no. 6 of Gwisan-Dong, Joseon grave no. 65 of Gaeumjeong, Joseon grave no. 69 of Gaeumjeong, Joseon grave no. 79 of Gaeumjeong, no. 17 of Gangok in Geoje (from the top left)

Table 1. Classificatory criteria for the typology of the bronze bowls. Classificatory criterion, type, notes, provenance, height of stand, I, <1.5cm, Goryeo grave nos. 3 and 5 of Gwisan-Dong in Changwon, no. 3 of Muchon in Jinju -mound 1, Goryeo grave no. 8 of Deokcheon-Dong in Busan, Goryeo grave nos. 2, 4 and 38 of Jukgok-Ri in Gimhae, II, >/=1.5cm, grave nos. 74 and 82 of Gaeumjeong in Changwon, grave no. 36 of Gwisan-Dong in Changwon, no. 156 of Muchon in Jinju -mound 1, and nos. 95, 98, 153 and 159 of mound 3, nos. 2 and 17 of Gangok in Geoje, nos. 2 and 5 of Jangpyeong in Geoje, profile of rim, A, inclined, Goryeo grave nos. 4 and 5 of Gwisan-Dong in Changwon, Goryeo grave nos. 4 and 5 Jukgok-Ri in Gimhae, grave nos. 41 and 69 of Gaeumjeong in Changwon, nos. 85, 95 and 98 of Muchon in Jinju -mound 3 and the other numerous sites, B, flared, Goryeo grave no. 5 of Gaeumjeong in Changwon, Goryeo grave nos. 3 and 67 of Gwisan-Dong in Changwon, grave nos. 38, 39 and 40 of Jukgok-ri in Gimhae, grave no. 18 of Deokcheon-Dong in Busan, no.114 of Muchon in Jinju -mound 1, and 64 and 159 -mound 3, C, vertical, Goryeo grave nos. 8, 13 and 45 of Deokcheon-Dong in Busan, grave nos. 41, 79 and 82 of Gaeumjeong in Changwon, no. 86 of Gwisan-Dong in Changwon, no. 8 of Jangpyeong in Geoje, manufacturing method of stand, 1, connected later, nos.

51, 67 and 69 of Gaeumjeong in Changwon, Goryeo grave nos. 3, 5, 82, 85, 86 and 91 of Gwisan-Dong in Changwon, no. 3 of Muchon in Jinju -mound 1, and 95 and 98 -mound 3, Goryeo grave no. 8 of Deokcheon-Dong in Busan, Goryeo grave nos. 2, 4 and 38 of Jukgok-ri in Gimhae and the other numerous sites, 2, casted at once, nos. 41, 74 and 78 of Gaeumjeong in Changwon, nos. 82, 85, 86 and 91 of Gwisan-Dong in Changwon, nos. 13 and 18 of Deokcheon-Dong in Busan, no. 114 of Muchon in Jinju -mound 1, and 64, 159 -mound 3, nos. 2 and 8 of Jangpyeong in Geoje (from the top left)

Table 2. Average heights of the bronze bowls and of their stands. Average heights of the bronze bowls and of their stands., Goryeo, height of the whole bowl, height of the stand, Joseon, height of the whole bowl, height of the stand, unit (from the top).

Table 3. The number of bronze bowls which have different rim profiles. The number of bronze bowls which have different rim profiles., Goryeo (18 specimens), inclined (5 specimens), flared (12 specimens), vertical (1 specimen), Joseon (44 specimens), inclined (25 specimens), flared (11 specimens), vertical (8 specimen) (from the left top).

Table 4. The number of bronze bowls of which the stand was made by different methods in the Goryeo and Joseon periods. The number of bronze bowls of which the stand was made by different methods, Goryeo (19 specimens), none (5 specimens), attached later (13 specimens), casted together (0 specimen), Joseon (45 specimens), none (14 specimens), attached later (15 specimens), casted together (16 specimens) (from the top left).

Table 5. Transformations of bronze bowl in the Goryeo and Joseon periods. Period, height of stand, low, high, method of attachment of stand, attached later, casted together, profile of rim, inclined, flared, vertical, Goryeo, Joseon (from the top left).

Table 6. Typological classifications of bronze spoon. Type, sharpness of curve of handle, form of end of handle, form of bronze spoon, provenance, Ⅰ、>/=2.2cm, middle of end of handle is opened in V shape and the end is pointed, grave b nos. 1, 2, 4, 5, 6 and 8 of Deokcheon-Dong ruins in Gupo, no. 3 of Muchon in Jinju -mound 1, Goryeo grave nos. 1 and 3 of Gwisan-Dong in Changwon, Goryeo grave nos. 1, 2, 4 and 5 of Gaeumjeong in Changwon, II, =/> 1.8cm and <2.2cm, middle of end of handle is opened in Y shape and the end is pointed, num.57 of Muchon in Jinju -mound 2 ・153 -mound 3, Joseon grave nos. 3 and 51 of Gaeumjeong in Changwon, grave no. 30 of Gwisan-Dong in Changwon, III-1, >/=1.2cm and <1.8cm, middle of end of handle is opened in Y shape and the end is angler, no.46 of Muchon in Jinju -mound 1, grave nos. 41, 78 and 80 of Gaeumjeong in Changwon, III-2, middle of end of handle is opened in V shape and the end is pointed, grave nos. 5 and 15 of Sinjun-ri in Gosung, grave nos. 97, 100 and 253 Deoksan-Ri in Gimhae, no. 63 of Muchon in Jinju -mound 2, grave nos. 4, 66, 68 and 86 of Gwisan-Dong in Changwon, III-3, middle of end of handle is opened in U shape and the end is angler, grave nos. 6 and 12 of Sinjun-Ri in Gosung, grave no. 12 of Jangpyeong in Geoje, grave nos. 1, 61 and 82 Deoksan-Ri in Gimhae, III-4, flatly widened handle from the middle, grave nos. 2, 4, 5, 6, 7 and 9 of Jangpyeong in Geoje, grave no. 19 of Sinjun-Ri in Gosung, grave nos. 1, 4, 7, 19 and 27 of Deoksan-Ri in Gimhae, grave b nos. 4, 20 and 24 of Deokcheon-Dong ruins in Gupo, recovered from the other numerous sites, IV, <1.2cm, straight handle to the end, nos. 2 and 17 of Gangok in Geoje, grave nos. 6, 7, 8 and 113 of Gwisan-Dong in Changwon

Table 7. Distributions of the degree of curvature and the ratio of the length of bowl to the whole length of bronze spoons. The degree of curvature (unit: cm), ratio of the length of bowl to the whole length” (from the top left)

Table 8.The averages in the degree of curvature and the ratio of the length of bowl to the whole length by type. The ratio of the length of bowl to the whole length, the degree of curvature (unit: cm) (from the top).

Table 9. Distributions of the dimensions of the bronze spoons. Unit: cm, Goryeo, Joseon, depth of bowl, length of bowl, whole length

# The Characteristics and Changes of Composition by the Periods on High Tin Bronze in Ancient Korea

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## *I. Introduction*

Bronze wares in ancient Korea first appeared in the end of the Neolithic period (1000-700 BC). So far, the earliest evidence of bronze wares have been discovered from pyramids in Egypt around 3700 BC. The technology of bronze wares of the Near East spread into the Mediterranean area, reaching Europe by around 3500 BC and Siberia by around 1500-700 BC[1].

Copper or major raw materials of bronze wares was one of the earliest metals, since the natural resources were refined with relatively little effort. Copper expresses reddish gloss on the surface. Malleable and ductile characteristics of the metal allow us to work easily, but the strength of finished products is often insufficient. For this reason, copper is alloyed in order to enhance the strength. Alloys of copper and tin, and copper and zinc are called bronze and brass respectively. Furthermore, leaded bronze and brass are called lead bronze and lead brass respectively. Bronze wares including larger proportions of tin are named high-tin bronze wares. Larger proportions of tin in the alloys enhance the strength and produce silver grey colour on the surfaces. High-tin bronze wares in Korea are represented by bronze mirrors. The bronze mirrors, as well as bronze daggers, are major indexes of periodization in Korean archaeology. Ancient casting techniques of bronze mirrors can be examined through proportions of major chemical components and observations of metallographic structures. Proportions of copper, tin and lead, change characteristics of the metal. In addition, different cooling rates and heat treatment processes form various metal structures even in the case of same chemical components. Minor components of the alloys are often impurities, but quantitative analysis of the substances reveals the degree of selection of raw materials, allowing us to assess intentional admixtures at the time of casting. Lead isotope ratios are used for the provenance assessment of lead[3].

These physical and chemical approaches to bronze artefacts from ancient Korea are currently developing. Yet small amount of the samples were merely analyzed, since collaboration between natural sciences and archaeology have thus far been insufficient. Thus, this paper compares archaeological characteristics of ancient Korean bronze mirrors with published physico-chemical data by different periods.

## *II. Archaeological characteristics of bronze mirrors in ancient Korea*

Bronze mirrors uncovered from Korea and northeastern Asian regions have no patterns on the mirror surfaces. Some mirrors with concave and convex reflecting surfaces have been attested, but mirrors with flat surfaces are common. The back surfaces include geometric incised patterns like coarse hatched or saw-toothed lines and concentric circles. The back surfaces also include two or three knobs. For this reason, these mirrors are called 'mirrors with multiple knobs', although two knobs were most common in the Bronze Age Korea[11]. In general, the mirrors consist of circular and square shape in plan. Based on usage, the mirrors are grouped into bronze mirrors, mirrors with handle, and mirrors with eyes. Circular or square bronze mirrors contain knobs on the center of the buck surface. Putting cord through the knobs, the bronze mirrors are taken by hands or caught on mirror racks. Mirrors with handle are used to reflect not only front face but also back shot, using two mirrors. Mirrors with eyes are hung or suspended, using the eyes[6].

### 1. Bronze Age[6), 15)]

Korean Bronze Age is generally divided into earlier and later phases. The ninth to seventh century BC is represented by violin-shaped bronze daggers and bronze mirrors with multiple knobs and coarse linear patterns. Bronze mirrors with zigzag or lightning patterns appeared during the sixth century BC. Cast bronze mirrors established and flourished during the later phase. In the period, bronze mirrors with more than two knobs have been discovered. Bronze mirrors with simple geometric linear patterns like zigzag were produced at the beginning of the Bronze Age. Yet the bronze mirrors were gradually replaced by bronze mirrors with fine linear patterns that consist of complex triangular and circular patterns. Finally, bronze mirrors with semi-circular rim cross section developed. In addtion, linear patterns were organized into inner, middle and outer sections.

**2. Early Iron Age and Proto Three Kingdoms period** [6), 15)]

The Early Iron Age in Korea started around the late third century BC or the early second century BC. Subsequently, iron production became common during the late first century BC. Since the period, many Han-style bronze mirrors were introduced through Lelang commandery into Korea. In addition, imitations of the Chinese bronze mirrors appeared in the south of the Korean peninsula. The Han-style bronze mirrors contain only one knob unlike bronze mirrors with coarse and fine linear patterns in the Korean Bronze Age.

In the Proto Three Kingdoms period (c. 0 to c. 300 AD), the states were systematically formed in Korea. Iron production rapidly developed during the period in order to make agricultural tools. The Han-style and local bronze mirrors increased in number.

**3. Three Kingdoms and Unified Silla periods** [6), 9), 15)]

Since the end of the Korean Three Kingdoms period, bronze mirrors have often been discovered from architectural features like temples, although mirrors were generally uncovered from tombs in previous periods. In the Silla region, bronze mirrors have not been attested during the third to fourth century AD or later, but limited number of small mirrors has appeared during the end of the fifth century AD to the sixth century AD. Until the middle sixth century AD, exotic mirrors were buried in elite tombs, while local mirrors were buried in tombs of relatively lower classes. The exotic mirrors were imported from Goguryeo until the middle fifth century AD. Later, Japanese bronze mirrors were imported. Bronze mirrors as burial goods markedly decreased since the middle sixth century AD, while mirrors have often been uncovered from temples. In the Baekje region, bronze mirrors were discovered from the tomb of King Muryeong. The Mireuksa Temple in Iksan also produced bronze mirrors.

Since the seventh century AD in the Unified Silla period, bronze mirrors were used as Sarira reliquaries. A decoration technique of imbedding of shapes cut out from gold or silver sheets appeared since the period. Fragments of bronze mirrors from the Mireuksa Temple in Iksan show characteristics of typical Tang-style bronze mirrors.

**4. Goryeo period** [6), 15)]

Abundunt bronze mirrors have been discoverd during the Goryeo period. Several definitions of the Goryeo-style bronze mirrors have been proposed. In general, the bronze mirrors of Goryeo are divided into mirrors with local designs, techniques, and materials of Goryeo, and imitations of Chinese bronze mirrors.

A bronze mirror with the raised inscription of “高麗国造” (the official of Goryeo) is a representative of the bronze mirrors in Goryo. The mirror was obviously fablicated in Goryoe, since no othre bronze mirrors in the period contain inscriptions of country names except Goryoe. Bronze mirrors without patterns in Korea often contain raised inscriptions of region names, suggesting the mirrors without patterns were typical bronze mirrors of Goryeo. Possible bronze mirrors of Goryeo also include mirror with the inscription of “煌丕昌天” (great and resplendent is the heaven) or with images of dragons, trees and a palace. Limited number of mirrors with the inscription of “煌丕昌天” have uncovered from China, but the mirrors have been well attested in Korea. In the case of bronze mirrors with images of dragons, trees and a palace, depth of raised patterns of the Korean mirrors is lower than the Chinese mirrors. In addition, images of the Korean mirrors are often reversed. On the other hand, the Chinese mirrors have no images of dragons.

## *III. Physico-chemical characteristics of bronze mirrors in Korea.*

**1. Chemical compositions**

Table 2 shows published chemical compositions of bronze mirrors by periods. The average values of the main components of bronze mirrors of the Bronze Age/the Early Iron Age, the Proto Three Kingdoms period/the Three Kingdoms period, the Unified Silla period, and the Goryeo period indicate 67.6% Cu, 26.7% Sn, and 5.4% Pb; 67.4% Cu, 28.0% Sn, and 4.6% Pb; 68.1% Cu, 26.8% Sn, and 4.7% Pb; and 68.4% Cu, 18.9% Sn, and 10.1% Pb respectively. Sn contents increased in the Proto Three Kingdoms/the Three Kingdoms periods, but the contents decreased in the Unified Silla period. Nevertheless, Sn contents in those periods show high proportions in general. On the other hand, Sn contents in the Goryeo period drastically decreased, while Pb contents increased. In general, high proportion of tin improves strength of the alloys. However, over 22% Sn contents reduce tensile strength of the alloy[4]. High proportion of tin also prevents impact resistance of bronze wares. Moreover, number of tin mines and amount of the deposits were quite limited in Korea[7]. On the other hand, low proportion of tin reduces reflectance of mirrors. Thus, in order to enhance degrees of whiteness of mirror surfaces, tin amalgams were used or the surfaces are soaked in molten metals like gold and tin. In this way, mirrors with high reflectance and impact resistance were apparently produced[13]. When these techniques were introduced into Korea? This question is still open to discuss, but the techniques have been frequently attested in later periods. Investigations of the questions are currently on-going.

Figure 1 shows distribution of Cu, Sn and Pb contents of bronze mirrors by periods in a ternary diagram. During the Bronze Age and the Early Iron Age, a regular pattern, which Pb contents are stabilized and Cu and Sn contents are inversely related, are confirmed. However, chemical compositions of bronze mirrors become diversified in later periods. In order to indicate the transition clearly, Figure 2 shows proportions of Cu and Sn contents. In general, Cu and Sn contents are inversely related from the Bronze Age to the Three Kingdoms period, forming a same line. Yet the points are dispersed during the Unified Silla period and the Goryeo period, suggesiting diversified techniques of the brozne mirror production in Korea.

**2. Metallographic structures**

Different fabrication processes of bronze mirrors yield particular metallographic structures. In addition, different raw materials and additives yield particular inclusions in the matrices. Thus, metallographic observations allow us to collect various information related to making processes of bronze mirrors.

Containing over c. 14wt% tin, bronze wares express bright silver colour on the surface and acquire strength. However, over c. 16wt% tin reduces the strength. Over c. 14wt% tin create two phases, while over c. 25wt% tin create three phases[2].

Bronze mirrors conducted both of chemical and metallographic examinations include a bronze mirror with multiple knobs and fine linear patterns (national treasure of Korea No. 141) and a bronze mirror with multiple knobs and fine linear patterns from Hyoja-dong in Jeonju in the Early Iron Age, and bronze mirror fragments from the Mireuksa Temple in Iksan in the Three Kingdoms and Unified Silla periods.

**1) Bronze mirror with multiple knobs and fine linear patterns (national treasure of Korea No. 141) in the Early Iron Age**[12]

The background mostly consists of the $\delta$ phase. The $\alpha$-$\delta$ eutectoid are formed between cracks of the $\delta$ phase. Larger and smaller grains correspond to pinholes and lead respectively. Grey grains represent $Cu_2S$. Corrosive substances in the pinholes located at the lower part contain re-deposited copper.

**2) Bronze mirror with multiple knobs and fine linear patterns from Hyoja-dong in Jeonju in the Early Iron Age**[14]

The microstructure of the cast bronze mirror consists of the $\delta$ grains and the dendrites of the $\alpha$-$\delta$ eutectoid. Bronze mirrors generally contain c. 22% Sn, but the mirror include 30.4% Sn. Perhaps for this reason, the $\delta$ phase was predominantly formed compared to the $\alpha$ phase. Small black grains represent lead, spreading whole of the matrix.

**3) Bronze mirror fragments from the Mireuksa Temple in Iksan in the Three Kingdoms and Unified Silla periods**[8]

a) The copperish part represents the $\alpha$ phase. The whitish part between cracks of the $\alpha$ phase corresponds to the $\alpha$-$\delta$ eutectoid. Examinations of the microstructure demonstrate that no evidence of forging and thermal treatments other than casting is observed.

b) The microstructure of the sample has a resemblance to Sample 1 described above. Bright yellow grains represent the $\alpha$ phase. The whitish part between cracks of the $\alpha$ phase corresponds to the $\alpha$-$\delta$ eutectoid. However, Widmanstätten patterns are formed in the part adjoining the surface of the mirror. This result suggests that cooling rate on the exterior part is more rapid than the interior part. No evidence of fabrication and thermal treatments other than Widmanstätten patterns is observed.

c) Yellow grains represent the $\alpha$ phase. The dendrites correspond to the martensite structures (dark parts represent the $\gamma$ phase). Bright aciculas consist of the $\beta$ phase. These results suggest that the temperatures of the sample preceding quenching reached the $\beta$ range. Contrast to other two mirror fragments, evidence of intentional quenching was observed.

**3. Lead isotope analysis**

Bronze wares mostly consist of copper and tin, but lead is also mixed into the alloys if required. The reasons to mix lead include improvements of fluidity and workability at the time of casting and an alternative material of tin, which might often be expensive and unavailable. Based on these technological and economic backgrounds, adequate amounts of lead were mixed into bronze wares. Temporal and spatial information of provenances of raw materials reveals various aspects of past human activities. Provenances of lead can be identified through analysis of lead isotope ratios[5].

Analyses of lead isotope ratios of eight Korean bronze mirrors have thus far been conducted. They are including a sample of the Bronze Age, five samples of the Early Iron Age, a sample of the Proto Three Kingdoms period, and a sample of the Three Kingdoms period, concentrating on the Early Iron Age. The results currently available may be insufficient in terms of quantity and typological attentions to the mirrors. Nevertheless, the information provides us some insights into attributes of the mirrors. Table 3 and Figure 3 summarize the results. Except the bronze mirror fragments from the Mireuksa Temple in Iksan in the Three Kingdoms period, three groups were formed along the same line. No temporal variability was observed from the results, but there is a contrast between bronze mirrors with multiple knobs and fine linear patterns (▲) and imitative mirrors (●). Although no morphological information for the fragments of the Three Kingdoms period was obtained, the samples belong to the range of Korean mirrors, suggesting that they consist of parts of bronze mirrors with multiple knobs and fine linear patterns.

## *IV. Summary and discussion*

In this paper, we explored characteristics of bronze mirrors excavated from Korean archaeological sites, focusing on the results of physico-chemical analysis of the mirrors.

First, temporal changes of chemical compositions were observed. In the later periods, tin contents of the mirrors tended to decrease, while lead contents increased. In the earlier periods, high-tin contents enhanced reflectance ratios of the surfaces of the mirrors, expressing silver grey colour. Later, some limitations of procurements of tin might reduce the contents in the alloys. In order to supplement this, tin amalgams were used or the surfaces were soaked in molten metals like gold and tin. Perhaps in this way, degrees of whiteness and reflectance ratios of the mirrors were enhanced, retaining impact resistance. Proportions of the main components of copper, tin, and lead were stabilized in the earlier periods, but the proportions became diversified in the later periods, suggesting technological transitions occurred in various ways.

Second, observations of metallographic structures demonstrated that the $\delta$ phase was predominantly formed instead of the $\alpha$ phase in the Early Iron Age samples, i.e., bronze mirrors with multiple knobs and fine linear patterns of the national treasure of Korea No. 141, and from Hyoja-dong in Jeonju in the Early Iron Age. Re-deposited copper has also occurred. The phenomena suggest the bronze mirrors included high-tin contents. A fragment of a bronze mirror of the Three Kingdoms period (Sample 3) contained the martensite structures, suggesting that intentional quenching were performed. Although results of metallographic analyses of Korean bronze mirrors have been limited, over 30% Sn contents in the Early Iron Age and presence of quenching technique in the Three Kingdoms period were confirmed.

Last, lead isotope analysis demonstrated different ranges between bronze mirrors with multiple knobs and fine linear patterns, and imitative bronze mirrors.

Apart from bronze mirrors, high-tin bronze wares include various types of artefacts. Phisico-chemical data of the wares currently available is insufficient, but further diverse investigations should reveal diachronic developments of high-tin bronze ware technologies in Korea in detail.

Table 1: Diachronic developments of bronze mirrors with multiple knobs[11)]

(From top left) Periods, Absolute dates, Developments of bronze mirrors, Early Violin-shaped Bronze Dagger period, 800-600 BC, Bronze mirrors with coarse linear patterns, Late Violin-shaped Bronze Dagger period, 600-400 BC, Initial Slender Bronze Dagger period, 400-300 BC, Bronze mirrors with coarse and fine linear patterns, Early Slender Bronze Dagger period, 300-200 BC, Middle Slender Bronze

Dagger period, 200-100 BC, Bronze mirrors with fine linear patterns, Late Slender Bronze Dagger period, 100-50 BC, Final Slender Bronze Dagger period, 50 BC-50 AD, Han-style bronze mirrors, Transformed Bronze Dagger period, 50 AD-100 BC.

Table 2: Chemical compositions of bronze mirrors[8), 13), 15)]

(1) Bronze Age and Early Iron Age: (from top left) No., Period, Provenance (Artefact register No.), Artefact, Cu, Sn, Pb, Zn, Fe, Ni, Sb, As, Bi, Co, Ag, Analyzed area, Analytical method, Reference

1. Bronze/Early Iron, Ryongsan-ri of Shinchon, Bronze mirror with fine linear patterns, 79.7, 16.0, 4.0, -, 0.04, 0.04, 0.15, -, 0.08, -, -, -, -, History of metallurgy in Korea (3) (2000)
2. Early Iron (national treasure of Korea No. 141), Bronze mirror with multiple knobs and fine linear patterns, 61.7, 32.3, 5.5, 0.16, 0.07, 0.16, -, -, -, trace, 0.23, Rim, XRF, Study of bronze mirror with multiple knobs and fine linear patterns (National treasure of Korea No. 141) (2009)
3. Early Iron, Baegam-ri of Hwasun, Bronze mirror with fine linear patterns, 65.1, 28.4, 6.3, 0.05, 0.01, 0.16, -, -, -, -, 0.04, -, -, -
4. Early Iron, Daegok-ri of Hwasun, Bronze mirror with fine linear patterns, 65.8, 28.6, 5.4, 0.05, 0.03, 0.16, -, -, -, -, 0.23, -, -, -
5. Early Iron, Daegok-ri of Hwasun, Bronze mirror with fine linear patterns, 65.3, 28.8, 5.7, 0.04, 0.03, 0.14, -, -, -, -, 0.16, -, -, -
6. Early Iron, Hyoja-dong in Jeonju, Bronze mirror with multiple knobs and fine linear patterns, 64.0, 30.4, 4.7, 0.02, 0.06, 0.06, -, 0.23, -, -, 0.40, -, -, 0.40, -, ICP, Chemical analysis of a bronze mirror with multiple knobs and fine linear patterns from Hyoja-dong in Jeonju, Jeollabuk-do (2006)
7. Early Iron, Wonboongni in Nonsan, Bronze mirror, 71.4, 22.6, 5.9, ≦0.02, 0.41, 0.86, 0.27, -, -, 0.05, -, ICP, Chemical analysis of Bronze wares from pit burials of Wonboongni in Nonsan (2003)

(2) Proto Three Kingdoms and Three Kingdoms periods

8. Proto Three Kingdoms, Jisan-dong in Daegu (Gukeun 8), Bronze mirror, 67.7, 24.2, 7.8, -, 0.16, -, -, -, -, -, -, Cross section, XRF, Bronze mirror collection of the Gyeongju National Museum (2007)
9. Silla, South Mound of Hwangnam Daecheong (Hwangnam 3340), Bronze mirror with inscriptions, 50.4, 44.7, 5.0, -, 0.03, -, -, -, -, -, -, -, Cross section, XRF, Bronze mirror collection of the Gyeongju National Museum (2007)
10. Baekje, Mireuksa Temple, -, 67.4, 25.8, 4.9, -, 0.25, 0.05, 0.14, 0.02, -, -, -, -, ICP, Metallurgical studies of bronze artefacts from the Mireuksa Temple (1992)
11. Baekje-Unified Silla Mireuksa Temple (Mireuksa 3), Fragment of bronze mirror, 75.3, 21.6, 0.5, 0.02, 0.41, 0.15, 0.50, -, -, 0.05, 0.58, -, ICP, Metallurgical and provenance studies of bronze mirrors from the Mireuksa Temple in Iksan (2007)
12, Three Kingdoms or Unified Silla, Seolbong Mountain Fortress in Icheon, -, c. 76.2, 23.8, -, -, -, -, -, -, -, -, -, -, EDS, Technological systems of bronze artefacts from the Seolbong Mountain Fortress in Icheon (2004)

(3) Unified Silla period:

13. Unified Silla, Mireuksa Temple (Mireuksa 1), Fragment of bronze mirror, 66.8, 22.9, 6.3, 0.01, 0.55, 0.15, 0.63, -, -, 0.08, 0.31, -, ICP, Metallurgical and provenance studies of bronze mirrors from the Mireuksa Temple in Iksan (2007)
14. Unified Silla, Mireuksa Temple (Mireuksa 2), Fragment of bronze mirror, 69.1, 24.9, 5.5, 0.01, 0.18, 0.13, 0.13, 0.29, -, 0.05, 0.06, -, ICP, Metallurgical and provenance studies of bronze mirrors from the Mireuksa Temple in Iksan (2007)
15. Unified Silla, Dongsanli of Cheonbug-myeon (Gyeongju 2499–1), Fragment of bronze mirror, 72.1, 25.6, 2.2, -, 0.10, -, -, -, -, -, -, Cross section, XRF, Bronze mirror collection of the Gyeongju National Museum (2007)
16. Unified Silla, Dongsanli of Cheonbug-myeon (Gyeongju 2499–2), Fragment of bronze mirror, 65.0, 28.2, 6.6, -, 0.23, -, -, -, -, -, -, Cross section, XRF, Bronze mirror collection of the Gyeongju National Museum (2007)
17. Unified Silla, Anapji in Gyeongju, (Anap 1031), Bronze mirror, 51.4, 42.9, 2.8, -, 3.10, -, -, -, -, -, -, Cross section, XRF, Bronze mirror collection of the Gyeongju National Museum (2007)
18. Unified Silla, Bunhwangsa temple in Gyeongju, -, c. 73.0, c. 27.0, -, -, -, -, -, -, -, -, -, EDS, Technological transitions of bronze wares from the Bunhwangsa temple in Gyeongj (2005)
19. Unified Silla, Bunhwangsa temple in Gyeongju, -, c. 74.0, c. 24.0, -, -, -, -, -, -, -, -, -, EDS, Technological transitions of bronze wares from the Bunhwangsa temple in Gyeongj (2005)
20. Unified Silla, Bunhwangsa temple in Gyeongju, -, c. 73.0, c. 19.0, -, -, -, -, -, -, -, -, -, EDS, Technologi-

cal transitions of bronze wares from the Bunhwang-sa temple in Gyeongj (2005)

(4) Goryeo period:

21. Goryeo, Main Building 2579, Bronze mirror with the inscription of 高麗国造 , 68.9, 16.5, 11.4, 0.28, 0.03, 0.27, 0.56, -, -, -, 1<, Matrix, XRF, Goryeo bronze mirrors: reflecting culture and life of the Goryeo people (2010)
22. Goryeo, Deoksu 89, Bronze mirror with the inscription of 高麗国造 , 71.3, 14.1, 13.9, 0.18, 0.04, 0.12, 0.41, -, -, -, <1, Matrix, XRF, Goryeo bronze mirrors: reflecting culture and life of the Goryeo people (2010)
23. Goryeo, Shinsoo 1358−41, Bronze mirror with the inscription of 煌丕昌天 , 71.4, 13.5, 14.3, 0.29, 0.03, 0.25, 0.32, -, -, -, 1<, Matrix, XRF, Goryeo bronze mirrors: reflecting culture and life of the Goryeo people (2010)
24. Goryeo, Deoksu 4927, Bronze mirror with the inscription of 煌丕昌天, 68.0, 31.3, 0.6, -, 0.03, 0.15, -, -, -, -, 1<, Matrix, XRF, Goryeo bronze mirrors: reflecting culture and life of the Goryeo people (2010)

Table 3: Lead isotope ratios of bronze mirrors[10)]

(From top left), No., Period, Site, Artefact, 206/204, 207/204, 208/204, 207/206, 208/206,

1. Bronze, Sudong site in Yeonggwang, imitative bronze mirror, 18.565, 15.695, 39.218, 0.8454, 2.1154
2, Early Iron, Nonsan, Bronze mirror with multiple knobs and fine linear patterns, 18.463, 15.664, 38.749, 0.8484, 2.0988
3. Early Iron, Wonboongni in Nonsan, Bronze mirror, 17.959, 15.635, 38.710, 0.8706, 2.1555,
4. Early Iron, -, National treasure of Korea No.141: specimen No. 18 of bronze mirror with multiple knobs and fine linear patterns (metal), 19.572, 15.887, 40.205, 0.8117, 2.0541,
5. Early Iron, -, national treasure of Korea No.141: specimen No. 5 of bronze mirror with multiple knobs and fine linear patterns (metal), 19.507, 15.845, 40.369, 0.8122, 2.0672,
6. Early Iron, Hyoja-dong in Jeonju, Bronze mirror with multiple knobs and fine linear patterns, 18.672, 15.963, 40.051, 0.841, 2.111,
7. Proto Three Kingdom, Yangdongri tumuli in Gimhae No. 427, imitative bronze mirror, 17.736, 15.539, 38.382, 0.8761, 2.1640,
8. Three Kingdom, Northern area of the Mireuksa Temple in Iksan, Bronze mirror fragment, 20.303, 16.006, 39.697, 0.7883, 1.9552

Fig. 1: Distribution of Cu, Sn and Pb in a ternary diagram. +: Bronze/Early Iron; ◆ : Proto Three Kingdoms/Three Kingdoms; ● : Unified Silla; ▲ : Goryeo

Fig. 2: Distribution of chemical compositions of bronze mirrors (Bronze/Early Iron, Proto Three Kingdoms/Three Kingdoms, Unified Silla, and Goryeo)

Fig. 3: Lead isotope ratios of bronze mirrors of diffrent periods (Bronze/Early Iron, Proto Three Kingdoms/Three Kingdoms, Unified Silla, and Goryeo)

# A Study on Refining and Production of the Ancient Chinese High-TinBronze

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Abstract: The high-tin bronze metallurgy highly developed in the ancient China. As for the metal refining, a refining method using potassium nitrate and bone marrow was discovered in the Ming Period. This method was used for production of bronze mirrors. As for the casting, metal smiths in Pre-Qing Period already noticed that voids in the metal texture affects the reflectivity of mirrors. In later periods, this problem was resolved by changing the thickness of mirrors and size of mirror knobs. As for heat treatments, some Spring and Autumn Periods casted bronze products such as mirrors and swords were quenched. The quenching increased the strength of the high tin bronze and decreased its brittleness to a degree. As for forging, a new forming technique consisting of forging and quenching was introduced in China by the Han Period at the latest. This greatly advanced the workability of the high-tin bronze. All of these show the high level of the bronze production technology in the ancient China.

Key-Words: High-tin bronze, refining, casting, forging, quenching,

In the ancient China, high-tin bronze artifacts appeared for the first time in the Xia Period (2070 BC to 16th century BC) ① . From the Xia Period to the Song Period (960 to 1279 AD), high-tin bronze was used as the raw material for ornaments, tools, weapons, musical instruments, mirrors and vessels. These high-tin bronze artifacts can be divided into two types; casted artifacts and forged artifacts although the former was predominant. Some of them were heat-treated by annealing, quenching and tempering. In addition, some of the casted artifacts were processed by the lathe. These suggest that the ancient Chinese high tin bronze artifacts clearly reaches a high level in refining, casting, mechanical processing and heat treatments. This paper will discuss the ancient Chinese high-tin bronze production in particular focusing on refining, casting, mechanical processing and heat treatments.

### *1. Refining of High-tin Bronze in the Ancient China*

As early as Shang (1600 to 1046 BC) and Zhou (1046 to 256 BC) Periods, the bronze technology were highly developed in China. In these periods, amounts of bronze artifacts were produced. These bronze artifacts are large and vivid and have precise ornamentations. Their surface is smooth and beautiful. In addition, the composition of theses bronze artifacts is also appropriate. These bronze artifacts suggest the developments of refining methods.

In China, the refining has been regarded as an important process in the bronze production. A number of ancient texts from the Pre-Qin Period through the Han and Wei Periods to the Ming Period described the refining. The developments of bronze refining in the ancient China can be divided into three stages. (1) The refining method called Xiaolianzhijingbufujian (消煉之精不復減); This method was popular in the Pre-Qin Period. (2) The refining method called Bailian (百鍊); This method was used in the Han, Wei and Liuchao Periods. (3) The refining method using potassium nitrate and bone marrow; This method became popular in the Ming Period. Ancient texts and inscriptions on the bronze artifacts suggest that the first two methods were applied not only to high-tin bronze but also to bonze while the last method was mainly applied to the high-tin bronze.

#### **The refining method of Xiaolianzhijingbufujian**

The text of Kaogongji, Zhouli says, “ 㮚氏為量，改煎金錫則不耗，不耗然後權之，權之然後準之，準之然後量之，量之以為鬴”. This text also says, “凡鑄金之狀，金與錫黑濁之氣竭，黃白次之，黃白之氣竭，青白次之，青白之氣竭，青氣次之，然後可鑄也”. The former argues that refining of copper and tin was necessary in order to cast measuring containers. It also introduced a series of stages to examine and improve the quality of the metal. Explanatory notes on “不耗” written by Zhengxuan in the Late Han Period says, “消煉之精不復減也”. The third volume of Mengxii Bitan written by Shenkuo in the Sung Period says,“百煉不耗”. The notes by Zhengxuan and text by Shenkuo are basically the same in the meaning although the former explains the refining method of copper and the latter explains refining method of steel. The second sentences of Kaogongji, Zhouli explain the condition of the flames in several stages during refining. Explanatory notes on these sentences written by Zhengxuan says, “消湅金錫精粗之候”. The text of Kaogongji is the textbook on crafts technology in Spring and Autumn and Warring State Period (1). The text contains a wide knowledge of metal refining and introduces technological standards. Explanatory notes by Zhengxuan imply that the measuring containers contained the same amounts of tin as Zhong (bells) and Ding (sacrificial vessels) and that the measuring containers probably contained 14.29% tin. This high percentage of tin is very close to that of high-tin bronze. The refining method called Xiaolianzhijingbufujian was probably a kind of multiple refining and metal was refined by repeats of the same process.

**(2) The refining method called Bailian**

In China, the multiple refining method with the Chinese character of “煉(Lian) ” appeared in the late Early Han Period. This method became commonly used in the Late Han and Liuchao Periods and continuously used after the Tang Period. Several types of this method such as “三煉 (Sanlian)”, “五煉(Wulian)”, “十煉(Shilian)”, “三十煉(Sanshilian)” and “百煉(Bailian)” are described in ancient texts. This method was used for production of bronze Ding, jars and mirrors. According to the text of Liuzai, Kaogonzi, the mirrors were made of high-tin bronze while Ding also contained amounts of tin.

The sentences of “前漢陽朔元年(24 BC), 上林十湅銅鼎” in the first volume of Hanjinwenlu written by Rong Geng is the oldest record of this multiple refining method in China. The volume also says, “永始二年(15 BC)，十湅銅鼎” and “永始三年 (BC14年)，十湅銅鼎”. The text of Fengcuang Xiaodu, which was written in 1121, says that one jar with the inscription of “前漢綏和元年(8 BC)，官造三十錬銅黄塗壺” was accidentally discovered. Some Late Han casted bronze artifacts also have inscriptions with “百煉”. A bronze mirror decorated with sacred animals and deities also has the inscription of “建安七年(202AD)九月廿六日作明竟，百湅青銅”. Liuchao mirrors often have inscriptions implying the multiple refining method. For example, Liuchao mirrors decorated with sacred animals and deities have inscriptions such as “黄初三年五柬”, “黄元年百湅明鏡”, “赤烏元年百湅正銅”, “黄龍元年陳師世造三湅明鏡”, “西晋太康元年百湅青銅” and “元康元年百湅正銅”.

The details of the Bailian method remain a mystery. However this method was probably a kind of the multiple refining. In the case of the modern casting, tin and copper are refined by the electrolytic refining to remove impurities before casting. In refining, to adjust the temperature and composition and to control the content of oxygen are the most important. In the ancient China, copper ores and tin ores were smelted by the method called “Huofa Zhilian”. The copper and tin smelted by this method contained a certain amount of impurities. Therefore the refining was regarded as an important process to remove impurities in the ancient China. The term, Bailian can be translated as a hundred repeats of refining. But the word does not mean that metal smiths indeed refined materials a hundred times. The second volume of Guoshibu written by Li Zhao says, “揚州旧貢江心鏡，五月五日揚子江心所鑄也，或言無有百煉者，功至六七十煉則易破難成”. These sentences are acceptable. The aim of multiple refining is to remove impurities and dozens of refining are not necessarily required. Through multiple refining, materials also absorb the oxygen. The more refining smiths undertake, the more oxygen the material absorbs. In particular, the material absorbs amounts of oxygen when the material is refined at a relatively high temperature. Too many repeats of refining cause overheated conditions on the material. The phrase of “易破難成” clearly points this condition, in which the grain boundary oxidation occurs.

**(3) The refining method using potassium nitrate and bone marrow**

The text of Kuaixuetangmanlu written by Feng Mengzhen in the Ming Period says, “凡鑄鏡，煉銅最難，先将銅烧紅打碎成屑，塩醋搗，荸薺拌，銅埋地中. 十七日取出，入炉中化清，每一両投磁石末一銭，次下火硝一銭，次投羊骨髄一銭. 将銅傾太湖沙上，别沙不用. 如前法六七次，愈多愈妙. 待銅極清，加椀錫. 每紅銅一斤加錫五両，白銅一斤加六両五銭，所用水，梅水及揚子江水為佳，白銅煉浄一斤只得六両，紅銅得十両，白銅為精”(2).

Both of “磁石 (magnetite)” and “火硝 (potassium nitrate) ” were oxidizing solvents. These solvents can remove airs (hydrogen) from the metallic solution. “羊骨髄 (bone marrow of sheep)” contains phosphorous and can be used as deoxidant. “椀錫” are zinc and can be used as protective solvents. The fourth volume of Jingjinglingchi written by Zheng Fuguang in the Qing Period says, “倭鉛即白鉛，又名

椀錫". The word of "椀錫" became a common term without ambiguous meanings after the Yuan Period. The process of this refining method will be explained here. First magnetite and potassium nitrate were put into copper solution in order to remove the oxygen. Second bone marrows of sheep were also put into this in order to remove the oxygen. Then zinc was put into the solution in order to reduce the oxidation of tin. Last tin was added again (3). This method is very sophisticated and basically the same as modern methods in principle. In fact, some modern copper workshops refine materials using the similar method and process. The sentences of "始前法六,七次" point two stages to remove the air and oxygen. The sentences suggest that these stages to remove the air and oxygen were repeated several times. It is likely that the stage of "塩醋搗，荸薺拌，銅埋地中" caused the increase of oxygen in the solution. As for the number of refining, the text says, "愈多愈妙". However this sentence is not reliable.

This text explained methods applied to the alloy for production of bronze mirrors. As for the proportion of copper and tin, the text says, "毎紅銅一斤加錫五両". It means that bronze mirrors contain 23.8% tin. This is very suggestive for understanding the Xiaolianzhijingbufujian method in the Pre-Qin Period, and Bailian method in the Han and Wei Periods. All of the three methods, Xiaolianzhijingbufujian method, Bailian method and method using potassium nitrate and bone marrow, were probably a kind of multiple refining method. These three methods represent three stages of the developments of bronze refining in China. There are differences to a degree between these three methods. (1) The methods were different in the details of the process and they were used in different periods. For example, the solution technique of zinc first developed in the Ming Period. Therefore the technique of adding zinc was not used in the Pre-Ming Period. (2) The composition of alloy is different between the three methods. The details of the process were also different. The composition of alloy effects the solution temperature and casting. For example, if bronze containing amounts of tin is used for production of mirrors, to reduce the content of oxygen in the solution is necessary in order to prevent oxidation of tin. This problem can be solved by adding zinc. Adding zinc also can stop the decrease of tin during firing. (3) These methods were used for production of different type of objects. For example, refining was necessary and important for the production of mirrors while refining was not necessarily important for the production of other objects.

***2. Casting of High-tin Bronze***

Currently bronze swords excavated from Majayao sites are the oldest casted bronze in China. They are dated to 3280 BC-2740BC. The oldest casted high-tin bronze artifacts are dated to the Xia Period and the early Shang Period. They were excavated from Huoshaogou sites[(4)], Yueshi sites[(5)], Erlitou sites[(6)(7)], Zhukaigou sites[(8)], lower Ziajiadian Chifen Dadianzi site[(9)] (Table1).

Some of the earliest high-tin bronze were probably obtained from paragenetic deposits of copper and tin. From the Xia to Tang and Song Periods, the high tin bronze was used as the raw material for ornaments (nose rings[(4)], earrings[(8)(9)], rings[(9)] and standards[(9)]), tools (farming tools and handicraft tools; hook[(7)], knife[(6)(8)], shaving knife[(10)], drill, needle[(14)], sickle[(18)], tearing knife[(19)], scraper[(22)], axe[(25)] and chisel[(26)]), vessels (Jue (cup)[(8)], Jia (cauldron), Gu (tall cup), Zun (sacrificial vessel)[(11)] and Ding), weapons (pike[(4)], dagger-axe[(8)(17)]), arrowheads and swords), musical instruments (zhong (bell)[(16)(26)], duiyu (drum)[(18)], Ling (bell)[(18)(26)]) and mirrors[(27)] (Table1). This strongly suggests that high-tin bronze was widely used in the daily life. A number of Chinese and international scholars have studied the bronze casting technology in the ancient China. The high-tin bronze has also been intensively studied by the scholars. This paper will not review the past studies here. The key topic of this paper is that ancient Chinese metal smiths noticed that voids in the metal texture affects the reflectivity of mirrors and that they developed some skills to resolve this problem.

Ancient mirrors suggest that there were regular changes in the size and thickness of mirrors, size of knobs, and the height of ornamentations from the Warring State Period through the Han Period to the Tang Period. It is generally argued that these changes can be explained by social trends and aesthetic reasons. When I published the book of "Zhongguo Gudai Tongjing De Jishu Yanjiu (A Technological Study on Ancient Chinese Mirrors)", I agreed with this idea. But I changed my idea and have a different idea now. There is probably another reason for these changes. This reason is probably related to voids in the metal texture, which appear during the solidification shrinkage of the metal. This paper will argue the chronological changes of the size of several parts of the bronze mirror. Samples were randomly chosen and mirrors from different periods were measured by the author. The samples include the mirrors excavated from the Hubei, Hunan, Anhui and Shaanxi provinces. I undertook the chemical composition analyses on most of the samples by myself [(28)]. The results of the measurements are as follows.

As for the size of mirrors, the mirrors in the Warring State Period are relatively small. After the Early Han Period, mirrors became bigger in size gradually. In the Late Han and Liuchao Periods, the size of mirrors became much larger than those in the preceding periods. In the Tang Period, mirrors became slightly smaller again. The author measures three Warring State Period mirrors (including the mirror with the decoration of mountains (No.1), which was excavated from Ezhou). Their diameter ranges between 94 and 144mm and the average of the diameter is 116mm. The author also measured three Ealy Han mirrors (including a Xin Period mirror (No.11) decorated with four deities, which is excavated from Ezhou). The average of their diameter is 128.7mm and they range between 98 and 128.7mm in diameter. 7 Late Han and Liu Chao mirrors (including a mirror decorated with deities and sacred animals (1-116), excavated from Ezhou) ranges between 103mm and 201mm and the average of their diameter is 161mm. 6 Tang mirrors (including a mirror with the decoration of flowers (2:3392), excavated Anhui) ranges between 106 and 188mm in diameter and their average diameter is 155mm [(28)].

As for the thickness of mirrors, Warring State Period mirrors were relatively thin and mirrors became thicker in the Han and Liuchao Periods.The author measured 6 Warring State Period mirrors (including a mirror (C1) excavated from Changsha). The thickness of these mirrors ranges between 0.8 and 1.2mm and the average thickness is 1.16mm. 5 Early Han mirrors (including a mirror with nipples (W8), excavated from Anhui) ranges between 1.28 and 2.8mm in thickness and their average thickness is 2mm. 6 Late Han and Liuchao mirrors ranges between 1 and 2mm in thickness and the average thickness of these mirrors is 1.517mm. 6 Tang mirrors (including a Bagua style mirror (E33) excavated from Ezhou) ranges between 2.9 mm and 4mm in thickness and their average thickness is 3.15mm [(28)].

As for the knob of the mirror, the knob of Warring State Period mirror is relatively small and short. The three string shaped knob is common in the Warring State Period. The average size of knobs of Warring State Period mirrors is 5m in length, 4mm in width and 7mm in height. In the Early Han Period, the knob became larger in size. In this period, the nipple shaped knob was popular. Their average size is 12mm in diameter and 7mm in height. Since knobs of Late Han and Liuchao mirrors are generally large and flat, they are called “large and flat circular knobs”. Their average size is 30mm in diameter and 10mm in height. The author also measure one large and flat circular mirror (mirror decorated with eight phoenixes [(32)] excavated from Ezhou). The size of the knob is 40.6mm in diameter and 5.0mm in height while the diameter of the mirror is 139mm. In the Tang Period, the knob also became slightly smaller. The author measured four Tang mirrors. Their size was 16mm (diameter)×5mm (height), 21mm×8mm, 20.5mm ×6.6mm and 25mm×10mm [(28)].

As for the height of ornamentations of mirrors, ornamentations of Warring State Period mirrors are relatively precise and low in height. The ornamentation varies in Warring State Period. The ornamentations include spiral motifs, triangle and circular motifs, flower-shaped motifs, T-shaped motifs and snake shaped motifs. After the Early Han Period, the ornamentations became higher and protruding. The common mirrors in Early Han Period were Riguang mirrors and Zhaoming mirrors. Ornamentations of Late Han and Liuchao mirrors are mostly protruding. In particular, the motif of sacred animals was preferred in these periods. Ornamentations of mirrors became less protruding in the Tang Period again.

These samples of the mirrors were randomly chosen. However, these samples probably reflect real changes of mirrors although there are some exceptional mirrors.

The changes cannot be fully explained by social trends or aesthetic reasons. In particular, the following questions are very difficult to answer. (1) Why are mirrors so small and thin in the Pre-Qin Period although ritual vessels in the period are thick? (2) Why are string holes not located in the center of the knobs although these mirrors are carefully produced after the Late Han and Liuchao Periods? These questions are very difficult to explain by social trends or aesthetic reasons. Research on modern crafts of casted bronze suggests that these changes can be explained by technical reasons. Theses changes probably occurred because metal smiths aimed to improve the reflectivity of mirrors, which is affected by voids in the metal texture.

The voids in the metal texture are caused by micro-shrinkage in a process of the casting. When the metal shrinks by cooling, $\alpha$ phase dendritic structures appear simultaneously, grow rapidly and spread out in the cross-hatched pattern. Micro metal liquid structures between the dendritic structures are separated from the dendritic structures when the dendritic structures are solidified and shrunk. Then the micro metal liquid structures cause scattered voids in the metal texture during the solidification shrinkage. The voids in the metal texture affect the casted bronze artifacts in two aspects. (1) The voids in the metal texture weaken the strength of casted bronze. However, given the ancient production technology, this problem was not so serious although bronze with voids were slightly unfavorable as weapons and craft tools. (2) The voids in the metal texture also affect the reflectivity of mirrors. If voids are created in the core of the mirror and on the ventral surface, the problem is not so serious. However, if the voids are created near the dorsal surface of the mirror, the problem is very serious. In this case, voids are exposed as amounts of micro pits when the dorsal surface is polished. The micro-pits are grayish black in colour.

The creation of voids and its number in the metal texture are decided by the conditions during the solidification shrinkage of the metal. There is no way to stop the creation of voids. However, the location of the voids can be controlled. Changes of mirrors through periods can be explained by considering the voids in the metal texture. Warring State Period bronze mirrors are relatively small and thin. It means that relatively small amount of metal was used for the production of Warring State Period mirror. Therefore mirrors could be rapidly cooled, shrunk and solidified. In this case, the number of micro metal liquid structures between dendritic structures was small and the amount of each micro liquid structure was also small. As a result, a small number of micro-pits were created in Warring State Period mirror. In addition, they were rarely created near the dorsal surface of the mirror. The knob of the Warring State Period mirror is also relatively small. As for the knob, the knob was solidified very slowly. Therefore there were no micro metal liquid structures between the dendritic structures. Voids were rarely created in the metal texture of the knob. These are advantages of Warring State Period mirrors. However, they also had week points. The mirrors were fragile and easily abraded. Therefore the mirror could be used only in a short term. From the Early Han Period to the Tang Period, bronze mirrors became bigger and thicker in size. The knob also became bigger. In the case of such mirrors, the core of the mirror was the hottest area during the casting. The area near the surface did not reach a high temperature like the core of the mirror, which reduced the affects of voids on the reflectivity of the mirror. In the Liuchao Period, the ornamentation of the mirror became larger and the string hole is not centered in the knob. These also could reduce the affects of the voids.

Ancient metal smiths controlled the location of voids by changing the size of mirrors, the size of knobs, the size of ornamentations and position of string holes. The smiths probably developed these skills over years. Voids appear in the both of the low tin bronze and high tin bronze. However the skill of controlling the location of voids was probably developed for the casting of high-tin bronze artifacts because (1) this skill was mostly used for the casting of high-tin bronze artifacts and rarely used for the production of other bronze artifacts and (2) under the same conditions, voids are more commonly created and larger in size in the high-tin bronze than in other bronze artifacts.

There is no way to stop the creation of voids in the metal texture. From the Han to Tang Periods, the bronze mirror became thicker and the ornamentation of the mirror also became larger. However, as a result, the mirror became too heavy to handle. After Wudai and north Song Periods, bronze mirrors contained relatively large amounts of lead and became lighter. These changes are also related to the affects of voids in the metal texture on the reflectivity of mirrors.

### *3. Forging of High-tin Bronze Artifacts and Lathe*

**(1) Forging of high-tin bronze artifacts**

Excavated artifacts suggest that most of the bronze artifacts in the Shang Period were casted bronze artifacts. In the Shang Period, forged bronze artifacts were rare. In particular, forged high-tin bronze artifacts were much rarer in this period. It is generally known that tin-bronze with less 30% tin is easily heat-treated. However, tin-bronze containing large amount of tin is very difficult to heat-treat. Currently the oldest forged high-tin bronze artifact are dated to the late Xia and early Shang Periods and contain Zhukaigou earrings (8) and lower Xiajiadian Chifeng Dadianzi earrings (9). The forged high-tin bronze artifacts from the Xia/Shang Periods to Ming/Qing Periods can be divided into five types; ornaments (earrings excavated from Zhukaigou and Chifengdadianzi), tools (bronze drill excavated from Jianchuan, Yunnan(14)), protective guards (armor excavated from Yangfutou, Kunming(21)), vessels (boat-shaped vessels excavated from Nanyan(29)) and musical instruments (Song bronze drums, cymbals excavated from Xueshansi, Xuzhou (30)and cymbals excavated from Jiangxi(31)) (Table 1). The ornaments, tools and protective guards are generally small and large sized ornaments, craft tools and protective guards were not produced. In contrast, the vessels and musical instruments are relatively large, which show the high-level of ancient Chinese bronze forging technology. Table 1 shows the composition of these forged high-tin bronze artifacts. The oldest forged high-tin bronze artifacts contain lead. For example, the earring of M453:2 excavated from Dadianzi contains 3.1% lead. The composition changed through the late Shang, Spring and Autumn and Warring State Periods. After these periods, the forged high-tin bronze artifacts contained no lead or little lead. This strongly suggests that ancient metal smiths already understood the nature of lead and bronze.

Figure 1 shows the metal texture of Early Han boat-shaped vessel of YN1 excavated from Nanyang. The needle shaped structures in the texture are $\beta$ phases processed by quenching. Light coloured agglomerates are $\alpha$ phase copper. This vessel was heat-treated by hot-forging and crystal grain boundaries are well developed. This is probably because the vessel was heated at a relatively high temperature and the temperature was kept for a long time (29). Figures 1-2, 1-3, 1-4 show the metal texture of the cymbal of DH: 2, drum of DH:5 and drum of DH: 4 excavated from Xuzhou. The first two objects were processed by hot-forging and quenching. The cross hatched needle shaped structures were the quenched structures and light coloured bar shaped agglomerates are $\alpha$ phase copper. Both of the objects suggest that they were quenched at a high temperature (586～798℃). The cymbal of DH：2 were probably heated at a relatively high temperature and the temperature was kept for a long time. As a result, crystal grain boundaries are well developed. The drum of DH：4 was processed by hot-forging and annealing. The texture are occupied by $\alpha$ phases. Patchy grayish white agglomerates were heat treated $(\alpha+\delta)$ eutectic alloy. Light grayish elongated objects are impurities. This suggests that the hot forging was undertaken at a relatively high temperature or the object was processed by annealing at a low temperature after hot-forging (31). The cross hatched needle structures and cross-hatched bar shaped agglomerates and circular objects, which are caused by quenching and tempering, are not observed.

The tenth volume of Tiangongkaiwu written by Song Yingxing in the Ming Period described the process of production of bronze cymbals. Even now, the similar techniques still exist over China such as Beijing (28) and Guangxi (32).

**(2) Lathe**

The lathe and grinder was first introduced into the production of high-tin bronze artifacts in the Han Period. The high-tin bronze artifacts processed by lathe can be divided into three types; (1) mirrors, (2) Vessels (e.g. boat shaped vessels), and (3) musical instruments (drums and cymbals). In addition, coins were also processed by the lathe.

The mirrors of 巻縁鏡 produced in the Han Period were mostly processed with the lathe and grinder. For example, the mirrors of 巻葉紋鏡 E1 and Early Han mirror (C3) with four nipples and snake shaped motifs, excavated from Changsha have clear traces left by the lathe and grinder. Both surfaces of these mirrors gleam black. The mirrors were entirely covered by these traces (27).

The boat shaped vessel of YN1, excavated from Nanyang is a typical high-tin bronze vessel processed by the lathe. Since most parts of this vessel are lost, it is difficult to reconstruct this vessel. Regular traces left by the lathe and grinder are visible on both surfaces of the vessel. In particular, traces on the outer surface are regular (Colored Plate1-1, 2). The convex outer face and concave inner face of this vessel undoubtedly made the process by the lathe more difficult (29).

Drums and cymbals excavated from Xueshansi, Xuzhou were typical musical instruments processed by the lathe. The author analyzed a set of the Song musical instruments, which were excavated from-Tongshan, Xuzhou in 1984. A total of four cymbals were excavated. They are well preserved. Traces left by hammering can be observed on the ventral surface and traces left by lathe can be clearly observed on the front face. Two cymbals measure 27.2 and 27.5 cm in diameter (Figure1-6). The drum of DH: 4 is circular shaped and its part is lost. The diameter of the rim is 21 cm. The drum measures 20 cm in diameter. It surfaces is filled with traces by the lathe (Colored Plate1-3). The drum of DH: 5 is deep bowl shaped and the rim measures 31 cm. It has a height of 19.3cm. Traces left by the lathe can be seen on the inner surface near the rim. The traces are very clear and regularly spaced (30) (31).

The above mentioned mirrors are casted bronzes and the boat shaped vessel and drums and cymbals are forged bronze artifacts. The boat-shaped vessel, drums and cymbals have distinctive traces by the lathe. This author believes that the traces were left not by casting but by turning machine tools such as lathe and grinder. Primitive turning machine tools were first appeared in the Liangzhu Period at latest. Some scholars suggest that they were used to work precious stones in Liangzhu Period and the technique spread into other regions soon after. The famous Tang silver vessel excavated from the village of Hejia show distinctive traces by the lathe. Even the start points and end points of work episodes can be observed (33). Song musical instruments such as drums and cymbals contains relatively large amount of tin and suggests a wide range of variations in types of large bronze artifacts and technological developments. Traces left on the surfaces and inner walls of the objects suggest the lathe technique reaches a quite high level. Further studies, in particular on machine tools, are still necessary.

***4. Quenching of High-tin Bronze Artifacts***

There are several different opinions on the origins of quenching technique in the ancient China. One report suggests that bronze shaving knife of TQ-01 excavated in Yuanqu, Shanxi Province, which is dated to the early Shang Period, is quenched (10). However, regrettably the figure of this knife in the report is too small to judge. Another report suggest that a part of the bronze sword of 3:1253, excavated in Gaochun, Jiangsusheng, which is dated to middle-late Zhou Period, is quenched although there are objections to this idea (15) (17).

Current evidence suggests that as late as the late Spring and Autumn Period the quenching technique was introduced in China. For example, the dagger-axe of 3:664 excavated in Dantu, Jiangsu Province, which is dated to the late Spring and Autumn Period, was undoubtedly quenched (Figure 2-1) (17). In Warring State Period, this technique highly developed and rapidly spread. From the Pre-Qin Period to Ming/Qing Periods, four types of bronze objects, weapons, mirrors, vessels and musical instruments were processed by quenching. In particular, mirrors were commonly quenched. From Warring State Period to Wudai Period, over 80% of mirrors were quenched and most of them show tempered texture (27).

The weapons showing quenched texture includes late Spring and Autumn Period dagger-axe excavated from Dantu, Jiangsu Province (3:664) , one 残戈 (fragment of dagger-axe)(17), early Warring State Period tearing knife of GL44 excavated from Luoding, Guangdong province (19), Warring State Period sword of J20 excavated from Jiangling (excavated from M131, Yutaishan)(23), Warring State Period bronze sword of LY1 excavated from Linyi, Shandong province (24), Warring State Period bronze scraper excavated from Emei, Sichuan province(22) and late Warring State Period/Qin/Han period bronze sword of MM 22: 6 excavated from Fuling, Xiaotianxi (Table1) (34). Figure 2-2 and Figure 2-3 show the metal texture of Warring State Period sword of J20 excavated from Jiangling (excavated from M131, Yutaishan) and Warring State Period bronze scraper of S22 excavated from Emei, Sichuan province respectively.

The quenching technique was first applied to production of mirrors by Warring State Period at latest and continuously used until Song Period (35). The samples suggest that the quenching was probably undertaken in $\alpha+\beta$ two phase region and $\alpha+\gamma$ two phase region. Figures 2-4, 2-5 and 2-6 shows the metal texture of Warring State Period mirror of J10 excavated from Jiangling, Late Han mirror excavated from Beijing and Tang mirror decorated with lotus of Sh3 excavated from the Shaanxi Province respectively. The first two mirrors was quenched at a high temperature (586~798℃). $\beta$ phases were changed into blue grey or brown needle shaped structures, bamboo-leaf shaped structures and circular structures by quenching and tempering. The patches and cotton-like structures among the above mentioned structures are $\alpha+\delta$ phases caused by tempering. The last mirror was quenched at a temperature between 520 and 586℃. Its metal texture show white cross-hatched bar shaped structures. These structures were $\alpha$ phases caused by quenching. Gaps between these structures are filled with gray agglomerates and cotton-like structures. These are $\gamma$ phases processed by quenching and tempering.

The Han boat-shaped vessel from Nanyan and cymbals and drums excavated from Xuzhou are typical quenched bronze artifacts (Figs. 1-1, 2, 3). Tin-bronze was probably quenched in order to strengthen the bronze and improve workability.

***Conclusions***

In the ancient China, the high-tin bronze technology first appeared in the Xia Period and highly developed in the late Shang Period. It reached a mature level in Spring and Autumn and Warring State Periods. This paper discussed refining, casting, forging, quenching and mechanical processing of the ancient Chinese high-tin bronze technology. As for refining, the Xiaolianzhijingbufujian method was used in the Pre-Qin Period and Bailian method appeared in the Han and Wei Periods. The method using of potassium nitrate and bone marrow developed in particular for production of mirrors in the Ming Period. As for casting, metal smiths in the Warring State Period already noticed that voids in the metal texture affects the reflectivity of the mirror. From the Han to Tang Periods, this problem was solved by changing the thickness of mirrors. As for forging, high tin-bronze forged artifacts made after the Late Shang Period, (by Spring and Autumn and Warring State Periods at the latest), contain no lead or only little lead. This strongly suggests that the metal smiths already knew that lead in tin-bronze affects its workability. As late as the Han Period, large and complex shaped vessels such as boat shaped vessels became to be produced by forging. In the Song Period, musical instruments such as drums and cymbals were produced by forging. In addition, the forging and quenching were combined to produce high-tin bronze artifacts in the Han Period, which greatly improved the workability of the high-tin bronze artifacts. As for quenching, the technique of the quenching first appeared in the late Spring and Autumn Period. They were used for the production of weapons such as dagger axes and swords and mirrors. In the Han and Song Periods, this technique was adopted for production of vessels and musical instruments. As for mechanical processing, high-tin bronze artifacts such as Han bronze mirrors and boat shaped vessels and Song drums and cymbals were processed by the lathe and grinder. Studies on the Chinese high-tin bronze production are very suggestive for understanding the reasons for the developments of the ancient Chinese civilization.

***Endnotes***

Figure 1

The metal texture of the Han boat shaped vessel of YN1 excavated from Nanyang (×250)

2. The metal texture of the Song cymbal of Dh:2 excavated from Xuzhou (×250)

The metal texture of the Song drum of Dh:5 excavated from Xuzhou (×500)

The metal texture of the Song drum of DH:4 excavated from Xuzhou (×500)

Traces left by the lathe on the ventral surface of the early Han 葉紋鏡 mirror of E1 excavated from Ezhou.

6. Traces left by the lathe on the dorsal surface of the Song cymbal of DH: 2 excavated from Xuzhou.

(1; Note 29, 2, 3, 4; Note 31, 5: Note 28,6; Note30)

Figure 2

1. The metal texture of late Spring and Autumn Period bronze dagger axe excavated from Dantu (×200).
2. The metal texture of Warring State Period sword excavated from Jiangling (×300)
3. The metal texture of Warring State Period bronze scraper excavated from Emei (×320)
4. The metal texture of a fragment of Warring State mir-

Table 1 Ancient Chinese High-tin Bronze Artifacts

| | Type・Sample Number | Site | Period | Composition（%） | | | | Production Method | Alloy type | References |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Copper | Tin | Lead | Others | | | |
| 1 | Circular headed sowrd | Erlitou | Erlitou Phase 3 | 82.3 | 15.4 | 1.3 | Ag0.186 As0.128 | | Tin bronze | -6 |
| 2 | Hook V H82：9 | Erlitou | Erlitou Phase 4 | 58.68 | 23.09 | 18.23 | | | Lead tin bronze | -7 |
| 3 | Drill T258㊄：7 | Yijiacheng | Yueshi | 71.11 | 15.12 | 13.78 | | | Lead tin bronze | -5 |
| 4 | Earring76 YHM299：21 | Huoshaogou | Siba | 84.2 | 15.8 | | | Forging | Tin bronze | -4 |
| 5 | PikeA045 | Huoshaoguo | Siba | 84.7 | 15.3 | | | Forging | Tin bronze | -4 |
| 6 | Earring（採集） | Zhukaigou | Phase 4 | 81.3 | 17.0 | <0.1 | | Heat treatment | Tin bronze | -8 |
| 7 | Dagger axe M1040：1 | Zhukaigou | Phase 5 | 80.0 | 15.0 | 4.7 | | Forging after casting | Lead tin bronze | -8 |
| 8 | Arrowhead H5003：11 | Zhukaigou | Phase 5 | 77.7 | 15.3 | 3.5 | Mg3.6 As1.4 | Casting | Lead tin bronze | -8 |
| 9 | Sword Handle H5028：1 | Zhukaigou | Phase 5 | 71.8 | 23.9 | 3.5 | Ag0.9 | Casting | Lead tin bronze | -8 |
| 10 | Jue H5028：5 | Zhukaigou | Phase 5 | 63.2 | 16.5 | 26.7 | Mg1.8 | Casting | Lead tin bronze | -8 |
| 11 | Earring M453：2 | Dadianzi | Lower Xiajiadian | 81.8 | 15.1 | 3.1 | | Hot-forging | Lead tin bronze | -9 |
| 12 | Earring M454：8 | Dadianzi | Lower Xiajiadian | 80.8 | 18.7 | | | Casting | Tin bronze | -9 |
| 13 | Earring M453：9 | Dadianzi | Lower Xiajiadian | 77.0 | 22.4 | | | | Tin bronze | -9 |
| 14 | 杖首M43：12 | Dadianzi | Lower Xiajiadian | 81.9 | 17.9 | | | | Tin bronze | -9 |
| 15 | Shaving knife YQ-01 | Yuanqu | Early Shang | 76.57 | 23.08 | 0.25 | | Quenching | Tin bronze | -10 |
| 16 | Jia 1802 | Panlongcheng | Panlongcheng | 71.2 | 16.7 | 9.5 | Zn1.6 | | Lead tin bronze | -11 |
| 17 | Gu 1810 | Panlongcheng | Panlongcheng | 55.7 | 18.2 | 24.4 | Zn0.8 | | Lead tin bronze | -11 |
| 18 | Zun 1820 | Panlongcheng | Panlongcheng | 63.57 | 15.3 | 17.77 | S1.0 Zn0.4 | | Lead tin bronze | -11 |
| 19 | Ding 96H1上：3 | Nanshungcheng g | Erlitou | 70.9 | 17.8 | 10.1 | | | Lead tin bronze | -12 |
| 20 | Sword 9H1≥1 | Zhangying | Middle Shang | 72.33 | 26 | 0.68 | | | Tin bronze | -13 |
| 21 | Drill CHT2≥3(47) | Haimenkou | Yin Shang | 82.1 | 16.6 | | | Hot-forging, cold forging | Tin bronze | -14 |
| 22 | Needle CHT2≥3(17) | Haimenkou | Ying Shang | 73.3 | 26.1 | | S0.4 | Casting | Tin bronze | -14 |
| 23 | Sword 3≥1253 | Gaochun | Middle/Late Western Zhou | 69.22 | 23.22 | 7.83 | | Quenching | Lead tin bronze | -15 |
| 24 | Bell M2≥1 | Zhechuan | Middle/Late Spring and Autumn | 77 | 15.3 | 7.26 | | | Lead tin bronze | -16 |
| 25 | Dagger axe 3≥664内 | Dantu | Late Spring and Autumn | / | 23 | / | | Quenching | Lead tin bronze | -17 |
| 26 | 残戈内 | Dantu | Late Spring and Autumn | / | 23 | / | | Quenching | Lead tin bronze | -17 |
| 27 | Sickle | Kunshanbingxi sheng | Late Spring and Autumn | 69.66 | 17.04 | 6.23 | | | Lead tin bronze | -18 |
| 28 | Drum 1 | Zhengjiangwa ngjiashan | Late Spring and Autumn | 66.62 | 26.2 | 4.63 | S1.03 Fe0.59 Si0.5 | | Lead tin bronze | -18 |
| 29 | Bell | Dantuqinglong shan | Spring and Autumn | 71.55 | 26.91 | 0 | | | Tin bronze | -18 |
| 30 | Tearing knife GL44 | Luo ding | Early Warring State | 79.46 | 19.5 | 1.04 | | Quenching | Tin bronze | -19 |
| 31 | 杓柄M4≥19 | Jingmenbaosh an | Middle Warring State | 83.388 | 15.733 | 0.469 | | Hot-forging, annealing | Tin bronze | -20 |
| 32 | Fragment of armour M101≥51 | Kunmingyangf utou | Middle/late Warring State | 82.5 | 16.8 | 0.8 | | Hot forging | Tin bronze | -21 |
| 33 | Scraper S22 | Emei | Late Warring State | 81.343 | 18,656 | | | Quenching | Tin bronze | -22 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 34 | Sword J20 | Jiangling | Warring State | 75.453 | 18.674 | 5.872 | | Quenching | Lead tin bronze | -23 |
| 35 | Sword LY1 | Linjyi | Warring State | 74.390 | 21.730 | 3.880 | | Quenching | Lead tin bronze | -24 |
| 36 | Axe B109 | Changsha | Warring State | 77.51 | 16.31 | 7.51 | | | Lead tin bronze | -25 |
| 37 | ChiselEC14 | | Eastern Zhou | 69.31 | 17.74 | 6.33 | Fe0.19 Zn0.1 | | Lead tin bronze | -26 |
| 38 | Bell EC1 | | Eastern Zhou | 73.26 | 17.72 | 8.53 | Zn0.07 | | Lead tin bronze | -26 |
| 39 | Bell EC17 | | Eastern Zhou | 73.73 | 17.45 | 8.45 | Zn0.08 | | Lead tin bronze | -26 |
| 40 | Mirror decorated with four mountains W1 | Anhui | Warring State | 78.779 | 19.684 | 1.536 | | Quenching | Tin bronze | -27 |
| 41 | 蟠螭紋鏡C8 | Changsha | Warring State | 77.294 | 21.343 | 1.361 | | Quenching | Tin bronze | -27 |
| 42 | Fragment of mirror J10 | Jiangling | Warring State | 78.826 | 21.173 | | | Quenching | Tin bronze | -27 |
| 43 | 巻葉紋鏡E1 | Ezhou | Early Early Han | 69.5 | 25.9 | 3.0 | | | Lead tin bronze | -27 |
| 44 | 四乳螭紋鏡C3 | Changsha | Early Han | 70.7 | 25.5 | 5.0 | | | Lead tin bronze | -27 |
| 45 | Boat shaped vessel, YN1 | Nanyang | Han | 79.0 | 18.73 | | Fe0.88 Si0.71 | Hot-forging, Quenching | Tin bronze | -29 |
| 46 | 連弧紋鏡B2 | Beijing | Middle/late Late Han | 68.827 | 27.337 | 3.834 | | Quenching | Lead tin bronze | -27 |
| 47 | Mirror decorated with Lotus, Sh3 | Fengxiang | Tang | 73.260 | 23.418 | 3.32 | | Quenching | Lead tin bronze | -27 |
| 48 | 許家六曲葵花鏡G1 | Jiangxi | Song | 63.778 | 27.473 | 7.041 | Si1.714 | Quenching | Lead tin bronze | -35 |
| 49 | 葉家六曲葵花鏡G3 | Jiangxi | Song | 69.65 | 25.76 | 4.59 | | Quenching | Lead tin bronze | -35 |
| 50 | Cymbal, G2 | Jiangxi | Song | 81.26 | 18.74 | | | Hot-forging, quenching | Tin bronze | -31 |
| 51 | Drum, DH≥4 | | Song | 79.12 | 17.96 | 0.81 | Fe1.1 Al1.01 | Hot-forging, annealing | Tin bronze | -31 |
| 52 | Cymbal, DH≥2 | Xueshansi, Xuzhou | Song | 79.89 | 17.92 | 0.12 | Fe0.78 Al1.3 | Hot-forging, quenching | Tin bronze | -31 |
| 53 | Drum, DH≥ 5 | | Song | 80.27 | 16.87 | 0.36 | Fe1.04 Al1.04 | Hot-forging, quenching | Tin bronze | -31 |

ror of J10 excavated from Jiangling (×320)

5. The metal texture of Late Han 連孤文 mirror of B2 excavated from Beijing (×320)

6. The metal texture of Tang mirror with ornamentation of lotus, Sh3 excavated from Fengxiang (×320)

(1; Note 17, 2; Note 23, 3; Note 22, 4, 5, 6: Notes 27 and 28)

Colored Plate 1

Traces left by the lathe on the outer surface of Han boat shaped vessel of YN1 excavated from Nanyang

Traces left by the lathe on the inner surface of Han boat shaped vessel of YN1 excavated from Nanyang

Traces left bu the lathe on the surface of the Song drum of Dh:4

Traces left by the lathe on the inner face near the rim of the Song drum of Dh: 5

(1, 2; Note 29. 3, 4: Provided by Dr. Li Yinde)

***Notes***

① The term of “high-tin bronze”is not still clearly defined. Its definition varies between scholars. In the 1980s and 1990s when I studied ancient Chinese bronze mirrors, I defined “high-tin bronze” as copper-tin alloy containing more than 15% tin, whose metal texture and metal quality was changed by quenching. This paper also adopts this definition. At that time I thought that the following three points were important. (1) The percentage of tin (15%) must be close to the critical point of $\beta$ phase precipitation (Tin 13.5%) on the equilibrium phase diagram. Otherwise this definition is theoretically meaningless. (2) The percentage of tin (15%) must be slightly higher, close to or slightly lower than the critical point of $\beta$ phase precipitation (Tin 13.5%) on the equilibrium phase diagram. Otherwise the $\beta$ phase content in the metal decreases and the quenching can change the metal texture and metal quality to a lesser degree. (3) Modern bronze artifacts containing more than 10% tin are also sometimes called as high-tin bronze for the convenience of recording.


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# Indian High Tin Bronzes: A continuing tradition from ancient to modern times

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***Abstract***

The elemental addition of arsenic or tin to pure metallic copper led to a revolution in the range of materials accessible to civilization and heralded the Bronze Age. A small addition of tin leading to low-tin bronzes brought beneficial attributes of low melting temperatures, The resultant ease of casting led to the lost-wax process. A higher amount of tin led to two classes of high-tin bronzes, namely beta and delta tin bronzes. At first they posed problems of brittleness. This challenge was successfully met by devising suitable thermo-mechanical treatments by heuristic methods and experimentation. It is over the last century that the scientific underpinnings of these processes are understood. This forms one theme of this paper. A second theme is the wide geographic spread and historical span of high-tin bronzes in India. There is growing evidence that the Indian compositions and processes spread across to the nations in Southeast Asia. Finally the continuity of the tradition in modern India will be touched upon.

## *1. Physical Metallurgy of Bronzes*

The mastery of bronze in antiquity is a remarkable chapter in human history. The phase diagram of Cu-Sn system was first established by Heycock and Neville in 1903. It was the second phase diagram of importance to be determined in metallurgy and followed that of Fe-C system by Roberts-Austen earlier in 1898. The Gibbs phase rule that governs phase equilibria was just beginning to be understood. It is an accomplishment that the first determinations were substantially correct. Figure 1 shows a modern version of this classic diagram. It will be seen that the diagram features several phases designated by the Greek letters a, b,c and d (Fig 2). The a phase is a solid solution of Sn in Cu with a face centered cubic arrangements as is copper. The addition of tin enhances strength. It has a pleasing golden colour as well. It is seen that the addition of Sn lowers the melting point and improves castability. This is ideally suited for making statues and icons. The b phase is an intermetallic with a body centered structure and is stable at high temperatures. It is termed a Hume-Rothery phase It has an ordered arrangement of copper and tin atoms. It is ductile and can be worked. Thus alloying leads to new intermetallics. Beta bronze is arguably the first intermetallic to be used by humankind. However slow cooling will lead to an eutectoid decomposition and result in brittleness. Rapid quenching from high temperature results in a martensitic phase with retained strength and ductility. This martensite structure depends on the composition. Their atomic arrangements are yet to be determined with the accuracy required. Sheer empirical experience led the ancient craftsmen to devising suitable thermo-mechanical treatment. This composition –15 to 25 % Sn- also leads to alloys for making bells due to the sonorous quality. Such alloys are called Bell Metal. Additional tin leads to Speculum Metal used for making reflectors and mirrors. Even more astounding is the use of the d phase. This is again an intermetallic with about 33% Sn. It has a very complex structure with 416 atoms and is classified as a structurally complex intermetallic. Its electronic state as Hume-Rothery phase is responsible for its optical property. It has a high reflectivity but alas is brittle. By casting narrow compositions in thin blocks an ingenious way was found to make the bronze mirrors. The structure of the phase is that of gamma brass and contains icosahedral clusters. The icosahedron is the most symmetric of all objects.

Though the beta phase occurs in a range of composition, it is believed that one unique composition correlated to the peritectic is the most suitable one. Cu-22% Sn is often used for bronze bells, gongs, cymbals, utensils. India, Thailand, Korea, Central Asia are known for forging and quenching in processing these alloys. Fig 3 shows the different

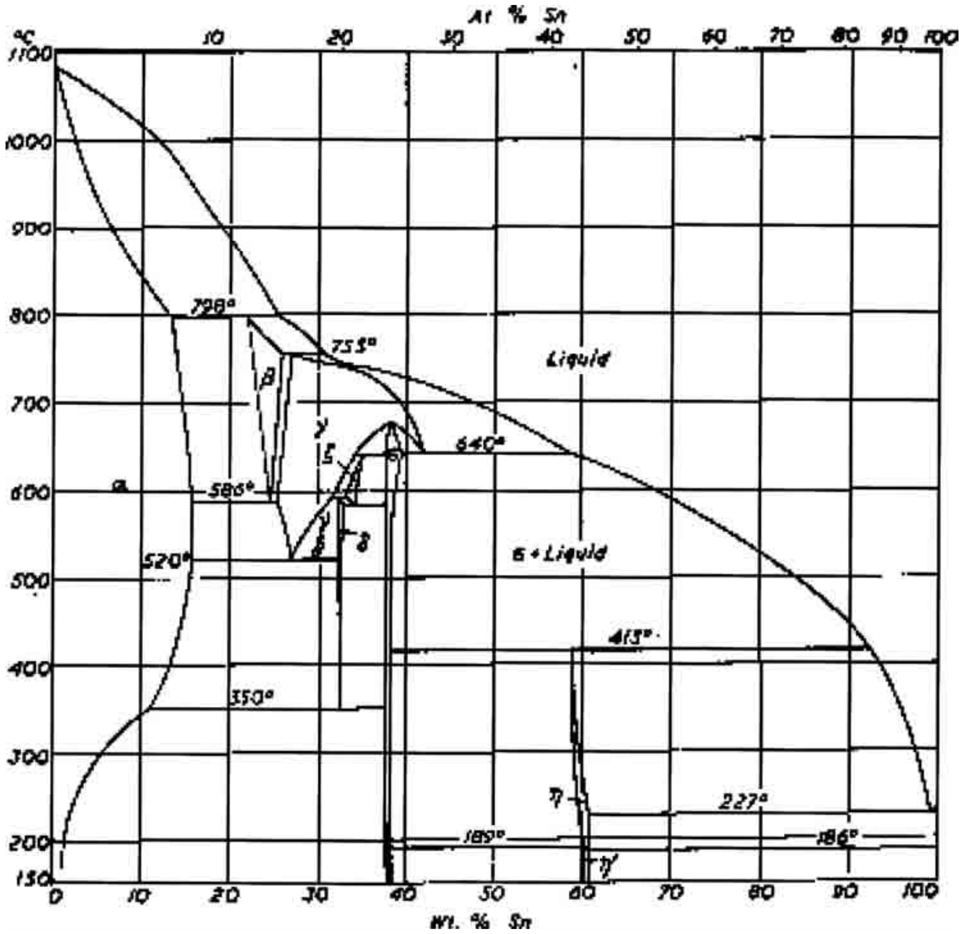


Fig.1. Equilibrium Phase Diagram of the Copper-Tin system under usual casting conditions.

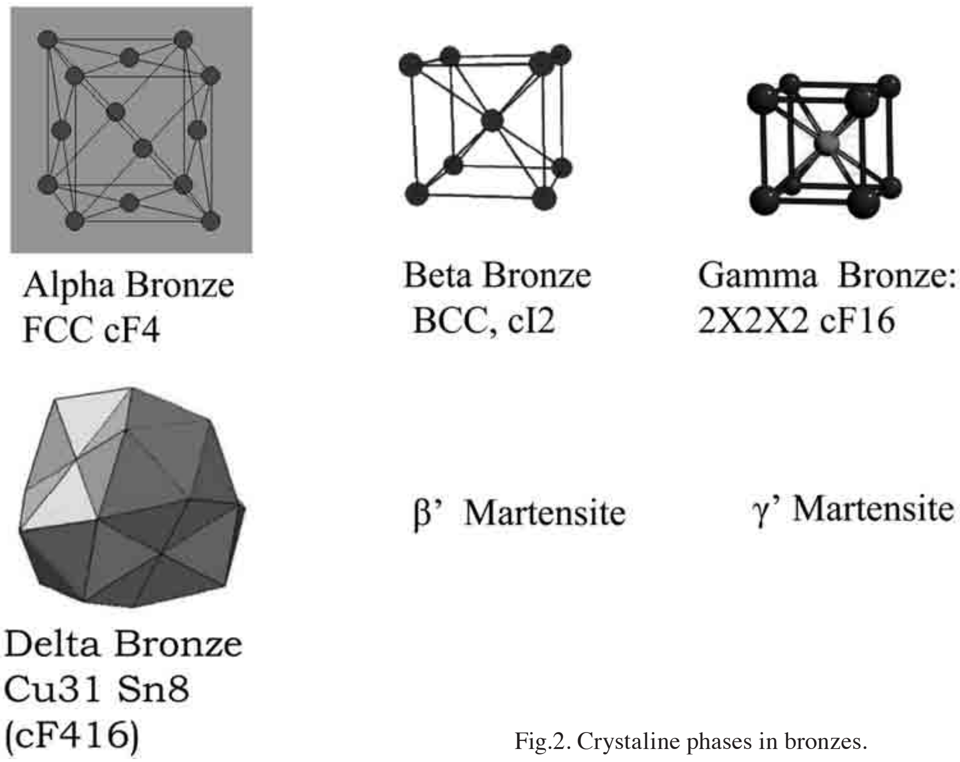


Fig.2. Crystaline phases in bronzes.

stages involved in making the Kadavaloor Utensils known in the Indian language Malyalam as Ottu Kinnam. The same procedures were also followed for Chengala Gongs for Kathakali, the celebrated dance form of Kerala.. Figure 4 shows wrought hammering of heated ingot of high-tin beta bronze (23% tin) in consecutive cycles in Palakkad, Kerala by hammering of red hot ingot in temperature range of formation of plastic beta phase (650-750℃). Figure 5 shows a modern high-tin beta bronze vessel from Payangadi (22.5% tin). A flat ingot of about 15 cm diameter was forged out into a large concave bowl of about 30 cm diameter. Figure 6 shows the microstructure of alpha plus beta martensite structure of hot forged and quenched beta bronze,at around 650 degrees. The annealing twins in the islands of alpha phase indicate a high degree of hot forging.

When the amount of tin is increased further, the delta phase appears. This is an excellent alloy for making metallic mirrors . India. China, Korea and Japan have long traditions in this alloy. It will be useful to make a comparison of the four nations to see any influence across space and time.

In the village of Aranmula, Kerala, an extraordinary metal mirror is traditionally made of delta high-tin bronze, of composition 32.6% tin. This is an ideal alloy to polish into a mirror due to the silvery colour and high hardness. The presence of this delta phase is optimized, and its high brittleness offset by a clever casting and polishing process. The unique feature of the bronze mirror is a front surface reflection, so the secondary reflections and aberrations typical of back surface mirrors are not present.

The entire Aranmula mirror manufacturing process seems to be geared at optimising the presence of the delta phase, which the copper-tin phase diagram indicates forms only within a narrow composition range of bronze of 32-34% tin at non-equilibrium room temperatures.  This silvery alloy shatters quite easily with something akin to brittle fracture in glass as observed by the authors with a thin cast blank. However, in the Aranmula mirror process this brittleness is offset not by adding lead

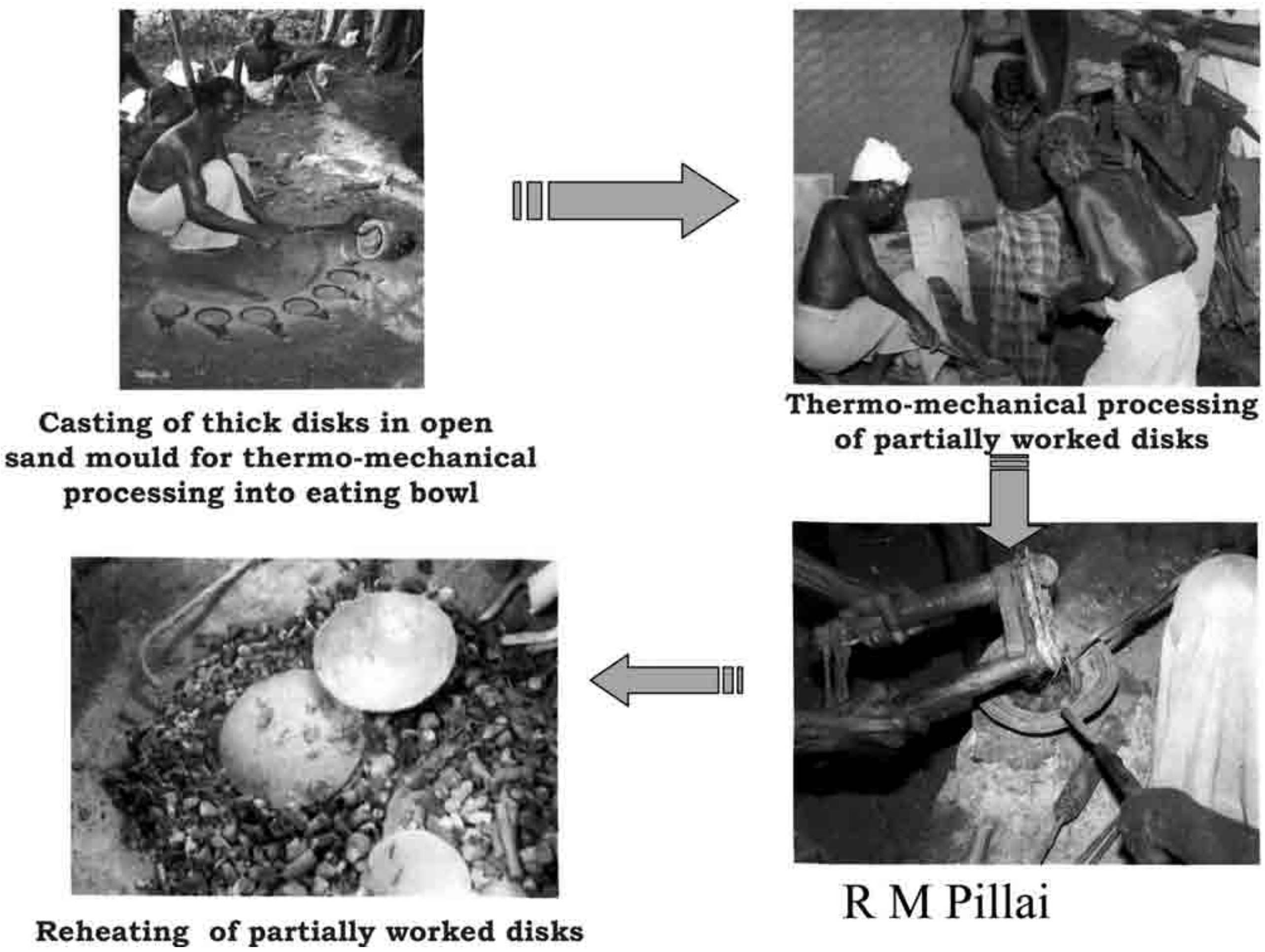


Fig.3. Kadavaloor Utensils (Ottu Kinnam) and Chengala Gongs for Kathakali (Courtest R M Pillai).

Fig.4. Wrought hammering of heated ingot of high-tin beta bronze (23% tin) in consecutive cycles in Palakkad, Kerala by hammering of red hot ingot in temperature range of formation of plastic beta phase (650-750℃) (Sharada Srinivasan).

but by casting a very thin blank, no more than 3 mm thick, which would thus cool more evenly with less heterogeneities than a thick specimen. Then this thin blank is reinforced by mounting it with resin on a wooden mount with a rear handle for the polishing process. A finished/polished mirror blank from Aranamula consisted of 32.5% tin, approximating the composition of the pure delta compound of 32.6% tin (Cu31Sn8). Figure 7 shows the cast oval (3 mm thick) blank of silvery delta high-tin bronze mounted with heated resin onto a wooden mount, to be polished to get the mirror effect(Sharada Srinivasn and Ian Glover 2007). Figure 8 shows the steps involved in manufacturing the mirrors. Fig 8 a shows crucible-cum-mould being sealed with cloth dipped in silt and straw/cotton wick Fig 8 b displays Inverted crucible-cum-mould, with the red hot mouth being packed with mud.

### *2. High Tin Bronzes of India*

Previously the well documented finds of quenched and lightly forged high-tin bronze had Glover in 1992.

Investigations undertaken at the Institute of Archaeology by Srinivasan in collaboration with Nigel Seeley and Ian Glover established the vessels to be of high tin beta bronze and the mirrors to be of unleaded ‘delta’ bronze ie 33% tin-bronze. Furthermore, metallurgical investigations of bronze vessels sampled by Srinivasan from Government Museum, Chennai uncovered from the Iron Age burials of Adichanallur and megalithic Nilgiri cairns (Srinivasan, 1994, 1998) and the Gandharan Graves obtained by Glover (Srinivasan and Glover 1995, 1997) showed evidence of some of the earliest known well developed usage of high-tin bronzes from megalithic contexts in peninsular and southern India (c. 1000-500 BC).

Comparisons between the hot forged and quenched high-tin bronzes from the Iron Age and megalithic sites in Tamil Nadu (Adichannallur and Nilgiris) and also observed in Palakkad indicated a high degree of hot forging and shaping before quenching in the micro-structures of the alpha plus

Fig.5. Modern high-tin beta bronze vessel from Payangadi (22.5%).
A flat ingot of about 15cm diameter was forged out into a large concave bowl of about 30cm diameter (Sharada Srinivasan).

Fig.6. Alpha plus beta martensite structure of hot forged and quenched beta bronze, at around 650 degrees. The annealing twins in the islands of alpha phase indicate a high degree of hot forging (Sharada Srinivasan).

come from tin-rich southeast Asia eg. Ban Don Ta Phet (c. 4th century BC) (Rajpitak and Seeley 1979). -Despite the analyses reported over a 100 years ago in Breeks (1873) of a few vessels from the Nilgiri cairns (associated with the south Indian megalithic) being of 20-25% tin-bronze, it was believed that these artefacts were imported (Leshnik 1974) and the possibilities of there being an local continuing tradition had not been considered due to the relative scarcity of tin in India.

In 1991, quite by chance, Sharada Srinivasan identified a rare continuing tradition of wrought and high-tin beta bronze vessel, in the village of Payangadi in Kerala (first reported in Archaeometallurgy of India conference 1991); this activity has sadly ceased in this village. In 1998 Srinivasan and Ian Glover visited Kerala and observed a workshops each for making wrought and high-tin beta bronze vessels and cymbals. The broader usage of unleaded high-tin bronze in Kerala was also established from observations of the making of mirrors by craftsmen from Aranmula by  Srinivasan in 1991 and by Ian

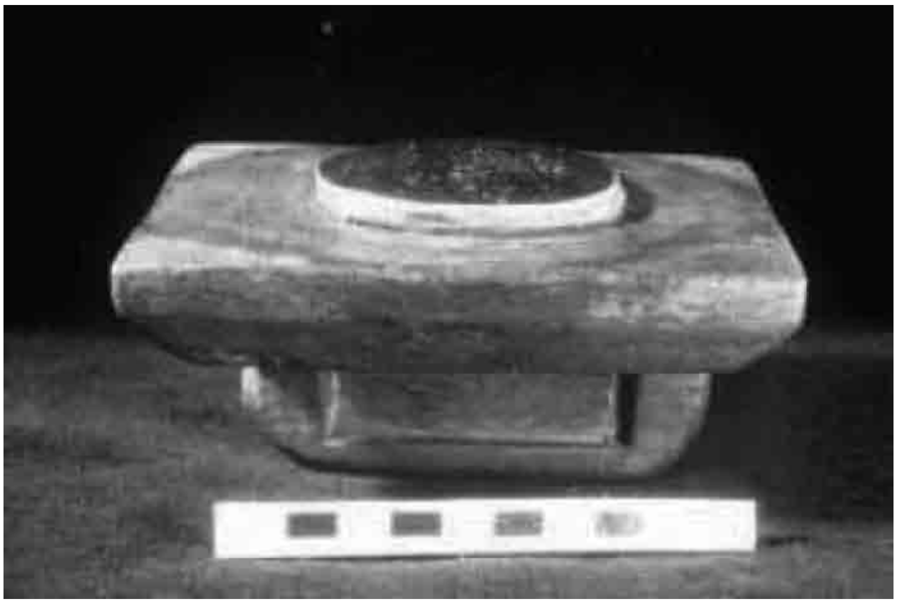

Fig.7. Cast oval (3mm thick) blank of silvery delta high-tin bronze mounted with heated resin onto a wooden mount, to be polished to get the mirror effect. (Sharada Srinivasan and Ian Glover Current Science, 93, 5 (2007))

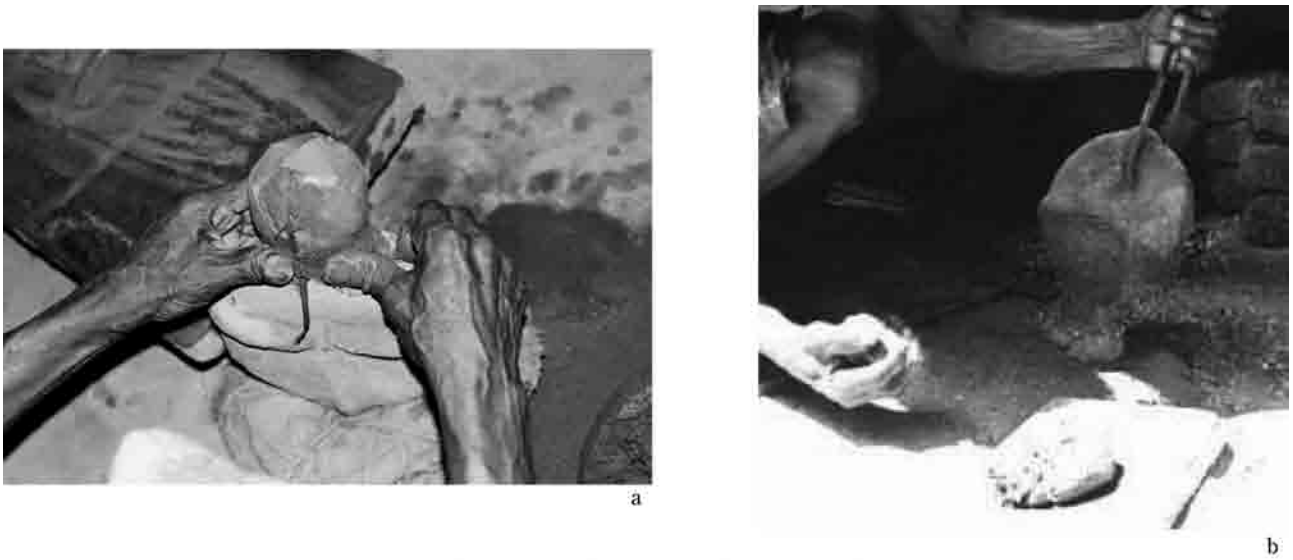


Fig.8. a: Crucible-cum-mould being sealed with cloth dipped in silt and straw/cotton wick. b: Inverted crucible-cum-mould, with the red hot mouth being packed with mud. (Sharada Srinivasan)

beta bronze (with pronounced annealing twins on well rounded alpha islands and very elongated beta needles) whereas in the case of the structures of many high-tin beta vessels studied from Ban Don Ta Phet by Warangkhana Rajpitak (Unpublished Ph D thesis, Institute of Archaeology, London) the degree of forging seemed to be a bit less and sometime these are only quenched with prominent as-cast dendritic structure in the alpha phase. A few of the Nilgiri and Adichanallur vessels have rims of 0.2-0.8 mm indicating extremely finely wrought work.

Rajpitak and Seeley (1979) have already pointed to a small number of copper alloy containers with similar compositions and forms in southern India – from the Nilgiri Hills; from Adichanallur; from Coimbatore in the Peninsula and from Taxila in Pakistan. Few of these are accurately dated although the ones from the Bhir Mound at Taxila are roughly contemporary with those from BDTP and KSK. Only the one bowl from Coimbatore was analyzed by Paramasivan (1941). It contained 23.6% Sn and was said to be typical of other vessels from the Nilgiris (Breeks 1873) and Adichanallur (Rea 1915)[1].

However, since the early 1990s metallurgical

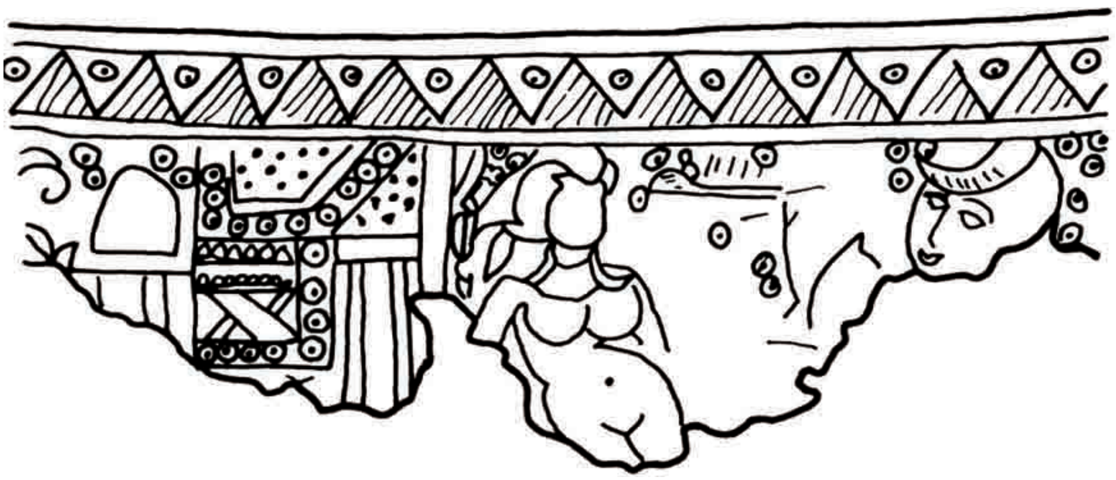

Fig.9. "Rim fragment of an incised decorated high-tin bronze bowl from Khao Jamook, western Thailand (Drawing by A. Bennett).

and ethno-archaeological studies made by Indian scholars (Pillai et al. 1994; Srinivasan 2010) on South Asian bronzes have documented the existence of high-tin bronzes from a range of contexts from prehistoric to the present day. These include objects excavated from Indian Megalithic and Iron Age contexts, some going back into the first millennium BCE. More recently Datta et al. (2007) have published details of a furnace for the manufacture of high-tin bronze at Tilpi in western Bengal. These, together with studies revealing continuing traditions of making high-tin bronzes, especially in Kerala of wrought and quenched high-tin bronze vessels and cymbals, suggest the regular use of unleaded bronze from very early stages of Indian prehistory (Srinivasan 2010).

Mirrors had both aesthetic value and magico-religious significance in parts of Asia, as in China and India. Bronze mirrors with figurines on handles are known from ancient Egypt. Flat, circular tanged mirrors were found from Harappan contexts northwest of the Indian subcontinent at Quetta and Harappa in Pakistan (ca. 2000 BC) and Dholavira in Gujarat, India. These would probably have been made of bronze of low tin content (i.e. <10% tin).

### *3. Thailand and Southeast Asia Connections*

High-tin bronzes were especially well documented from Thailand from the site of Ban Don Ta Phet and Khao Jamook, circa 4th century BCE through research of W. Rajpitak, N.Seeley, I. Glover and A. Bennett. .Within Southeast Asia, bronze vessels with this composition and similar forms have been recovered from the tin-gravels of western Malaysia (Batchelor 1978); in Thailand at Ongbah cave on the Kwae Yai River (Sørensen 1973: fig. 22), at Pak Beung, Ratchaburi Province (Bennett and Glover 1992); at Ban Pong Manao in Lopburi Province (Natapintu pers. comm.); at KSK in Chumphon Province (Murillo-Barosso et al 2010). Similar vessels have also been found at Prohear in eastern Cambodia (Reinecke et al. 2009); Dong Son inhumations and Han period brick tombs in northern Vietnam and from Tien Lanh, a late Sa Huynh burial in Central Vietnam (Bui Chi Hoang. 2008). Vessels decorated with very similar complex designs have so far only been found at BDTP, KJ and KSK. Fig 9 shows a rim fragment of an incised decorated high-tin bronze bowl from Khao Jamook, western Thailand.

Although there are similarities between the recent working processes and that which Rajpitak and Seeley (1979) inferred from their examination of the high-tin containers from BDTP, there are also significant differences. First, the ingots for bowl making in present-day Kerala are cast in open moulds, not by lost-wax casting in investment moulds, and the Kerala craftsmen do not so extensively grind down and polish the inner and outer surfaces to leave them smooth. However, the evidence of hot working is clear to see in the finished product. And the complex decoration cut into the outer surfaces with a grinding wheel in Thailand has not been reported in India except perhaps on the unique vase from Kundla in the Kulu Valley, north India which is reported to be of a ternary, not a high-tin alloy[2].

At present it still cannot be demonstrated for certain whether this distinctive alloy was developed independently in Thailand where tin and copper sources are abundant, or was introduced from South Asia in the mid first millennium BCE, but far more high-tin bronzes have been found and identified in Thailand and elsewhere in Southeast Asia than in South Asia.

### *4. Continuity and contemporary bronze Manufactories*

A remarkable feature of the Indian tradition of high-tin bronzes is the continuity from Iron Age sites and meglithic contexts of southern India. These include Nilgiri megaliths and cairns, the Adichanallur Iron Age burials and the Megalithic excavation of Mahurjhari of the earlier part of the first millennium BCE. Ethnoarchaeological studies by Srinivasan and Glover in the early 1990s clearly established the continuity of the traditions in modern day Kerala. Craddock and Hook (2007) have given further testimony to the continuity of these traditions. This is comparable to the 1000 year old tradition of lost wax casting of low-tin bronzes in Swamimalai in Tamilnadu. Additional studies show the survival of the bronze craft in eastern and western India.

The present collaboration of the authors with H Mifune, T Nagae and Y Shimizu brings modern tools to bear on the processing routes adopted by the Kerala artisans

### *5. Summary*

Indian bronze craftsmen have shown sufficient ingenuity in devising thermo mechanical treatments so that high-tin beta bronzes can be made into utilitarian objects. Similarly in dealing with the brittle delta-bronze for making mirrors they devised strategems in casting and polishing. This master y becomes all the more admirable, as a continuity in these processes can be seen spanning the past two millennia in different regions of India. It is also becoming evident that these technologies diffused to Southeast Asia and in particular to Thailand by religious and trade exchanges. Modern analytical techniques such as lead and tin isotope studies promise to provide further evidence to thee inferences.

### *Acknowledgments*

The authors would like to acknowledge Dr Nigel Seeley, Dr Anna Bennett, Dr Tom Chase, Prof V.N. Mishra, Dr R M Pillai, Dr Pranab Chattopadhyay and the Government Museum, Chennai, for their kind support in these research endeavours. It is also a pleasure to acknowledge collaboration with our colleagues from Japan,, Prof H Mifune, Prof T. Nagae and Prof Y Shimizu. Support for the Heritage Science Programme from Prof V S Ramamurthy, National Institute of Advances Studies, Bangalore is specially thanked. In some sections the text f follows the trend of ideas in earlier papers by the authors.

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**(Endnotes)**

1 Leshnik (1974: 156) gives the composition of some South Indian bronze bowls as: Adichanallur - Cu 75%, Sn 23%, Pb 0.2%, Fe 0.4%.; Maula Ali - Cu 79%, Sn 21%. Rajpitak and Seeley (1979: 29) refer

to the analysis of a bowl from Coimbatore which had a tin content of 23.58%.

2 The Kundla vase was found in the 19th century in a ruined Buddhist temple and is in the British Museum has not been exhaustively studied and only a superficial examination of the surface indicated a ternary composition (M. Hughes letter of 3rd February 1986 in British Museum records, courtesy M. Willis).

# インドの高錫青銅器：古代から現代に続く伝統

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**要旨**

純粋な銅にヒ素あるいは錫を混ぜることによって、人々が利用できる金属の幅が革命的に広がり、青銅器時代の幕開けとなった。少量の錫の追加は低錫青銅を生成するが、融点を低める効果をもたらした。それは鋳造を容易にし、やがてロストワックス法が生じた。多量の錫は2種類の高錫青銅を生み出した。それはβとδ高錫青銅である。当初は脆弱性の問題があった。しかし、試行錯誤により適切な熱工学的処理が考案され、この問題は解決された。この工程の科学的根拠が理解されたのは前世紀である。これが本稿の第1テーマである。2つ目は、インドにおける高錫青銅の広範な時空的分布についてである。インドの高錫青銅の構成と工程が東南アジア諸国にもみられるという証拠が増加している。最後に、現代インドに続く高錫青銅の伝統についてふれる。

## 1．青銅の物理冶金学

古代の青銅技術の発達は人類史における画期である。銅と錫の相図はHeycockとNevilleによって1903年に初めて提出された。冶金学において重要なのは2つ目の相図であり、それは1898年のRoberts-Austenによる鉄と炭素の相図に続いた。相平衡を司るギブスの相律が理解され始めた頃であった。素晴らしいことに、最初の同定はおよそ正しかった。図1はこの古典的相図の現代版である。相図にはギリシャ文字のaとb、c、dで表される相が示されている（図2)。a相は、錫と銅の固溶体で、銅と同じ面心立方格子構造を有する。錫を足すことによって強度が増し、魅力的な金色も呈する。錫の混入によって融点が下がり、鋳造がより容易になる。これは偶像などの製作に適している。b相は体心立方格子構造の金属間化合物であり、高温でも安定している。それはHume-Rothery相と呼ばれ、銅と錫の原子が規則配列されている。それは可鍛性を有し、加工可能である。こうして合金が新たな金属間化合物に至る。ほぼ間違いなく、b青銅は人類によって最初に使用された金属化合物である。しかし、緩やかな冷却は共析分解に至り、結果として青銅は脆弱になる。高温からの急冷により、硬さと可鍛性を有するマルテンサイト相になる。このマルテンサイト構造は青銅の構成に依る。その原子配列についてはこれから正確に同定される必要がある。古代の工人は経験により、適切な熱力学処理を考案した。この構成（15-20%の錫）は音響上の性質により、鐘の製作のための合金にもなった。そのような合金は鐘銅(ベルメタル)と呼ばれる。さらに錫を加えると、反射鏡などの製作に使われるスペキュラム合金に至る。さらに驚くべきはd相の使用である。これもまた金属間化合物で、33%の錫が混じる。416の原子による非常に複雑な構造を有し、構造上複雑な金属化合物に分類される。Hume-Rothery相としての電子状態が、その光学特性を生み出している。それは高い反射性を持つが、残念なことにもろい。特定の構成の青銅を薄く鋳造することによって、青銅鏡が巧みに製作された。この相の構造はγ真鍮と同じであり、二十面体クラスターを含む。二十面体は最も均整のとれた物体である。

β相は様々な構成で生じるが、包晶に関連する構成が最適と考えられている。銅と錫22%が頻繁に青銅の鐘や鼓、シンバル、器具に使用される。これらの合金の加工における鍛造と焼き入れで有名なのが、インドとタイ、韓国、中央アジアである。図3は、Kadavaloor器具（インド語のMalyalamでOttu Kinnamと呼ばれる）の製作工程を示す。同じ工程が、Kerala州の有名な舞踏であるKathakaliに用いられる Chengala鼓の製作でも用いられた。図4は、Kerala州のPalakkadにおいて、高錫β青銅(錫23%)の熱したインゴット(650-750度の可鍛β相)を連続的に鍛造している様子を示す。図5は、Payangadiの現代の高錫β青銅容器(錫22.5%)である。直径約15cmの平らなインゴットから、直径約30cmの大きな凹型の容器が鍛造によって作られた。図6は、約650度に熱しで鍛造され急冷されたβ青銅のαプラスβマルテンサイト構造の微細構造を示す。α相における焼きなまし双晶が、高温の鍛造を示す。

錫の量がさらに増すと、δ相が現れる。これは鏡の製作に最適な合金である。インドと中国、韓国、日本にはこの合金の長い伝統がある。時空的な影響があったかどうか、4カ国のあいだで比較するのは有益であろう。

Kerala州のAranmula村では、32.6%の錫を含むδ高錫青銅から素晴らしい鏡が伝統的に製作されている。この合金は研磨れて鏡になるが、銀色と高い強度のために理想的である。このδ相は最適化されており、巧妙な鋳造と研磨法により脆弱性が補われている。青銅鏡の特色は表面反射である。よって、背面鏡に典型的な背面反射や収差は伴わない。

Aranmula村の鏡の製作工程は、δ相の存在を最適化するように調整されているようである。銅と錫の相図によると、非平衡の室温において錫32-34%の青銅の狭い構成幅の中に納まる。この銀色の合金は、著者が薄い鋳造品に見たように、ガラスのぜい性破壊と同じように簡単に割れる。しかし、Aranmulaの鏡製作工程では、この脆弱性は鉛を混ぜることではなく、3mmという非常

に薄い鋳造品をつくることで補われる。薄い鋳造品は均一に冷却し、異質性が減少する。そして、この薄い鋳造品は、取手付きの木製台に樹脂で取り付けられ、研磨される。こうして完成したAranamulaの鏡は錫32.5%を含み、32.6%の錫を含む純粋なδ化合物（Cu31Sn8）に近い。図7は、銀色のδ高錫青銅の楕円形の鋳造品（厚さ3mm）で、木製台の上に熱した樹脂で取り付けられ、鏡として反射するように研磨されるところである（Sharada Srinivasn and Ian Glover 2007）。図8は、鏡を製作する工程を示す。図8aは、るつぼ付きの鋳型（crucible-cum-mould）で、シルトに浸した布と藁か綿の芯でふさがれている。図8bは、逆さにされたるつぼ付きの鋳型（crucible-cum-mould）で、赤く熱せられた口が泥で覆われている。

## ２．インドの高錫青銅器

以前は、焼き入れされ軽く鍛造された高錫青銅器は、錫が豊富な東南アジアからよく報告されていた（例えばBan Don Ta Phet、紀元前４世紀）（Rajpitak and Seeley 1979）。Breeks（1873）が100年以上前に報告した分析では、南インドの巨石文化に伴うNilgiri積石塚 から出土した容器は20-25%の錫と銅であったにも関わらず、インドに錫が比較的少ないという理由から、それらは在地の伝統ではなく輸入品だと考えられた（Leshnik 1974）。

1991年に偶然にもSharada Srinivasanは、Kerala州のPayangadi村において鍛造の高錫β青銅容器の製作伝統が続く貴重な例を発見した（それは初め、冶金考古学のインド大会で1991年に報告された）。しかし、その伝統は残念にも消滅した。1998年にSrinivasanと Ian Gloverは、Kerala州を訪問し、鍛造の高錫β青銅容器とシンバルを製作する工房を調査した。Aranmula村の工人による鏡の製作の観察から、Kerala州の無鉛高錫青銅の広範な使用が確認されたのは、1991年のSrinivasanと1992年のIan Gloverによる。

考古学研究所においてSrinivasanとNigel Seeley、Ian Gloverが行った分析によって、その容器は高錫β青銅であり、鏡は無鉛のδ青銅（つまり錫33%と銅）であることが分かった。さらに、SrinivasanがChennaiの博物館から採取した青銅容器は、Adichanallurの鉄器時代墳墓と巨石文化のNilgiri積石塚（Srinivasan, 1994, 1998）出土、およびGandharan墓からGloverによって得られたものであるが（Srinivasan and Glover 1995, 1997）、その金属学的分析の結果、半島と南インドの巨石文化（紀元前約1000-500年）において最も古く発達した高錫青銅であることが分かった。

鉄器時代とTamil Naduの巨石文化遺跡（AdichannallurとNilgiris）出土、それにPalakkadで見られる鍛造・焼き入れの高錫青銅器を比べると、焼き入れの前に加熱鍛造と成形がされている。それは、αプラスβ青銅の微細構造（円形のα領域上の焼なまし双晶と針のように細長いβ領域）に示される。しかし、Warangkhana Rajpitak（ロンドン大学考古学研究所の博士論文）が研究したBan Don Ta Phet出土の高錫β青銅容器の構造の場合、鍛造の度合いはやや低く、しばしばα相の顕著な鋳造（as-cast）樹状構造と共に焼き入れされるのみである。NilgiriとAdichanallurの容器の幾つかは、口縁が0.2-0.8mmの厚さであり、非常に精巧な鍛造である。

RajpitakとSeeley（1979）は、同様な構成と形態の銅合金製容器が南アジアにおいて少数存在することを既に指摘している。具体的には、Nilgiri Hills、Adichanallur、半島のCoimbatore、パキスタンのTaxilaである。これらのほとんどは正確に年代が与えられていないが、TaxilaのBhir MoundはBDTPやKSKと大体同時期である。Coimbatore出土の容器１点のみがParamasivan（1941）によって分析された。それは、23.6％の錫を含み、Nilgiris（Breeks 1873）やAdichanallur（Rea 1915）の容器も同様であると報告された[1]。

しかし、1990年代初頭からインド人研究者によって南アジアの青銅器に対して行われた金属学的・民族考古学的研究の結果（Pillai et al. 1994; Srinivasan 2010）、先史時代から現代にかけて存在した高錫青銅器が記録された。これには、紀元前１千年紀にさかのぼるインドの巨石文化や鉄器時代のコンテクストから発掘された遺物が含まれる。より最近では、西ベンガルのTilpiにおける高錫青銅製作用の溶鉱炉についてDatta et al.（2007）が詳細を報告した。これらは、Kerala州における鍛造・焼き入れの高錫青銅容器とシンバルの製作伝統に関する研究とともに、インドの先史時代の初期から無鉛青銅が規則的に利用されていたことを示す（Srinivasan 2010）。

鏡は、中国やインドなどアジアの一部において美的・呪術的重要性を有した。取手に偶像の付いた青銅鏡は古代エジプトから知られる。円盤状で柄のついた鏡はインド亜大陸北西部のハラッパー文化のコンテクストにおいて、パキスタンのQuettaやHarappa（紀元前約2000年）、インドGujarat州のDholaviraから発見された。これらはおそらく、少量の錫（つまり10%以下）を含む青銅製である。

## ３．タイと東南アジアとの関係

高錫青銅器は、タイで特に詳しく記録されており、それ は W. Rajpitak やN.Seeley、I. Glover、A. Bennett によって調査された紀元前約４世紀のBan Don Ta PhetやKhao Jamook遺跡出土である。東南アジアにおいて、この構成で類似した形態の青銅容器が発見されるのは、西マレーシアの錫礫層（tin-gravels）（Batchelor 1978）やタイのKwae Yai川のOngbah洞窟（Sørensen 1973: fig. 22）、Ratchaburi地方の Pak Beung（Bennett and Glover 1992)、Lopburi地方のBan Pong Manao（Natapintu pers. comm.）、そしてChumphon州のKSKである（Murillo-Barosso et al 2010)。類似した容器が発見されているのは、東カンボジアのProhear（Reinecke et al. 2009)、北ベトナムのDong Son文化の墓や漢時代の煉瓦墓、そして中央ベトナムの後期Sa Huynhの墓であるTien Lanhである（Bui Chi Hoang. 2008)。同様に複雑なデザインで装飾された容器がBDTPやKJ、KSKからもこれまで発見されている。図9は、タイ西部のKhao Jamook出土の刻文付き高錫青銅容器の口縁部破片である。

現代の製作工程は、RajpitakとSeeley（1979）がBDTPの高錫青銅容器の分析から推測した工程と類似している点もあるが、重要な違いもある。まず、現代のKerala州における容器製作用インゴットは開放鋳型による鋳造であり、インベストメント鋳型によるロストワックス法ではない。また、Kerala州の工人は内外の表面をそれほど丹念に研磨してなめらかな表面をつくらない。しかし、加熱加工は完成品に見る限り明らかである。そして、タイにおける回転砥石を用いた外壁への複雑な刻文はインドでは報告されていない。例外は、北インドKulu渓谷のKundla出土の特殊な容器である。それは高錫合金ではなく、三元化合物であると報告されている[2]。

現在のところ、この特別な合金が、錫と銅の産地が豊富なタイで独自に発達したのか、それとも紀元前1千年紀の中頃に南アジアから伝播したのか確実には分からない。しかし、南アジアよりも圧倒的に多くの高錫青銅がタイや東南アジアの各地で発見されている。

### 4．現代の青銅器工房への継続

高錫青銅器のインドにおける伝統について特筆すべきは、南インドの鉄器時代や巨石文化のコンテクストからの継続である。これに含まれるのは、Nilgiri積石塚や鉄器時代のAdichanallur墓、紀元前1千年紀初頭のMahurjhariの巨石文化の発掘である。1990年代初頭のSrinivasanとGloverによる民族考古学的研究は、現代Kerala州における伝統の継続を明らかにした。CraddockとHook（2007）によって、この伝統の継続に関する証拠がさらに提出された。これは、Tamilnadu州のSwamimalaiにおける低錫青銅のロストワックス法の1000年におよぶ伝統と比較しうる。東西インドにおいて青銅技術が継続していることが、さらなる研究で示されている。三船氏や長柄氏、清水氏と著者の共同研究は、Kerala州の工人が採用した製作工程に関する現代の道具を扱っている。

### 5．まとめ

インドの高錫青銅工人は巧みに熱力学的処理を行い、高錫$\beta$青銅から道具を製作することができた。同様に、もろい$\delta$青銅から鏡を製作するために、特別な鋳造と研磨を考案した。この技術は称賛に値する。というのも、インドの各地において過去2000年間これらの工程が継続したからである。これらの技術は、宗教や交易活動によって東南アジア、特にタイに伝播した。鉛や錫の同位体分析などの現代の分析を行えば、さらなる証拠が得られるであろう。

### 謝辞

Dr Nigel Seeley、Dr Anna Bennett、Dr Tom Chase、Prof V.N. Mishra、Dr R M Pillai、Dr Pranab Chattopadhyayそしてチェンナイの博物館から本研究に対しご厚情を賜りましたことを感謝申し上げます。三船教授と長柄教授、清水教授との共同研究にも謝意を表します。また、バンガロール国立高等研究所のV S Ramamurthy教授のHeritage Science Programmeから有りがたいご援助を賜りました。本文は部分的に、著者らの先行論文のアイディアに沿っています。

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図版キャプション

図 1：通常の鋳造条件下における銅と錫の平衡相図

図 2：青銅の結晶相

図 3：Kadavaloor 器具（Ottu Kinnam）と Kathakali に用いられる Chengala 鼓（R. M. Pillai より）

図 4：Kerala 州の Palakkad において、高錫 β 青銅（錫23％）の熱したインゴット（650-750 度の可鍛 β 相）を連続的に鍛造している様子

図 5：Payangadi の現代の高錫 β 青銅容器（錫 22.5％）。直

径約 15cm の平らなインゴットから、直径約 30cm の大きな凹型の容器が鍛造によって作られた。

図 6：約 650 度に熱して鍛造され急冷された β 青銅の α プラス β マルテンサイト構造の微細構造を示す。α 相における焼きなまし双晶が、高温の鍛造を示す。

図 7：銀色の δ 高錫青銅の楕円形の鋳造品（厚さ 3mm）。木製台の上に熱した樹脂で取り付けられ、鏡として反射するように研磨されるところである（SharadaSrinivasn and Ian Glover 2007, Current Science, 93, 5）

図 8a：るつぼ付きの鋳型（crucible-cum-mould）。シルトに浸した布と藁か綿の芯でふさがれている。

図 8b：逆さにされたるつぼ付きの鋳型（crucible-cum-mould）。赤く熱せられた口が泥で覆われている。

図 9：タイ西部の Khao Jamook 出土の刻文付き高錫青銅容器の口縁部破片（A. Bennett による図）

**(Endnotes)**

1　Leshnik（1974: 156）が示した南インドの青銅容器の構成は次の通り。Adichanallur － Cu 75%、Sn 23%、Pb 0.2%、Fe 0.4%。Maula Ali － Cu 79%、Sn 21%。Coimbatore の容器の分析結果を引用した Rajpitak と Seeley（1979: 29）によると、錫は 23.58%。

2　Kundla の容器は 19 世紀に廃寺から発見され、大英博物館に所蔵されている。表面観察のみによって、三元化合物だといわれている（大英博物館記録 1986 年 2 月 3 日の M. Hughes の手紙。M. Willis のご教示による）。